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Desk study to evaluate contributory causes of the current yield plateau in wheat and oilseed rape

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Project Report No. 502

Desk study to evaluate contributory causes of the current 'yield plateau' in wheat and oilseed rape

by

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1. ABSTRACT

To address the lack of progression in UK average farm yields for wheat and oilseed rape, national yield trends were analysed in relation to cropped area, genetic improvement, weather patterns, economic influences, crop nutrition and protection, plus other aspects of agronomy. Farm-specific data were evaluated to investigate the effects of changes or differences in agronomic practice, and research evidence examined to quantify their likely yield impact. Opportunities for overcoming yield constraints were considered, in the context of legislative, environmental and technical barriers, along with potential impacts on grain quality or end use.

From 1980 to 1996, wheat yields improved rapidly, by an average of 0.10 t/ha per year, aided by a fall in the proportion of second wheats. Since then, yields have stagnated despite the potential of new varieties increasing by 0.05 t/ha per year. A number of weather variables have influenced annual yield variation. Increased crop protection measures have minimised yield loss from weeds, pests and diseases, while a move to earlier sowing has contributed positively to yield. The transition to reduced tillage may have had a negative yield effect in the short term, with a longer-term impact possible from deep soil compaction. Crop nutrition has also been a factor in yield limitation, as a result of sub-optimal applications of nitrogen (N) fertiliser in at least some situations, and the area of crop receiving sulphur (S) fertiliser initially rising more slowly than the area at risk of deficiency.

From 1984 to 1994, oilseed rape yields declined but, after varying wildly, they have improved since 2004. Yield potential has increased at nearly 0.05 t/ha per year through genetic improvement but prior to 2004 poor uptake of higher-yielding varieties meant that over half of this was not being deployed. Increased cropping frequency has undermined yield improvement over the whole period. From 1984 to 1994, the net impact of agronomy was negative, with decreasing N fertiliser doses and increasing S deficiency. An increase in spring oilseed rape and unfavourable weather patterns also reduced yield improvement. From 1994 to 2004, yields benefitted from rising S fertiliser use but a shift to shallow cultivation was detrimental. From 2004 to 2011, better uptake of new varieties, strengthening crop protection and favourable weather combined to give a rising yield trend.

No single factor has had a dominant influence on yield trends. Changes to agronomy have had a number of mainly small effects, with growers aiming to maximise profit not yield. To restore rising yields in the face of warmer conditions, economic or environmental pressures and evolving weeds, pests or disease threats, a more holistic approach to agronomy is needed. Recommendations include improving selection and management information for varieties, sowing wheat earlier on light land to mitigate drought and a focus on improving N use efficiency. Benchmarking of yields, resources to 'health check' cropping systems and increased utilisation of survey data are vital to guide and measure change. Further studies should include the yield effects of changing weather, the incidence and severity of deep soil compaction and pollination and seed set in oilseed rape.

2. SUMMARY

2.1. Introduction and aims

The period from the 1940s to the 1990s saw exceptional growth in wheat yields. Improvements to farming methods, plant breeding and agronomy led to national average yields rising from 2.7 t/ha to 7.6 t/ha; 1 t/ha per decade, as the crop area doubled to 2.0 M hectares. Since then farm wheat yields have stalled, varying between 7.0 and 8.0 t/ha but with no rising trend. Oilseed rape yield trends have been complicated by the change from lower yielding spring varieties to higher yielding winter varieties and the introduction of low erucic acid (single-low) and then low glucosinolate (double-low) variety types. Since the double-lows became standard in the 1980s, farm yields have fluctuated wildly, with those of the mid-2000s little different to the 1980s. There has since been a hint of a rising yield trend, with the highest ever national oilseed rape yield in 2011 (3.9 t/ha).

With its favourable environment for achieving high yields and an efficient farming industry, the UK is well placed to respond to the challenges of rising global food demand. Genetic gain delivered by plant breeders has progressed at more than 0.5% per year for wheat yield and 2% for oilseed rape but farm yield trends suggest that either plant breeding benefits are not being realised on farm, or they are being negated by losses due to weather related effects or agronomic limitations.

The aims of this study were to identify agronomic factors that may be constraining wheat or oilseed rape yield improvement, assess the scope and opportunities for raising national yields through agronomy and highlight knowledge gaps or barriers to be addressed. Specific objectives included:

1. A review of existing evidence for agronomy as a contributory cause of yield plateau in wheat and oilseed rape, in the context of genetic improvement and changing weather patterns.
2. The examination of farm yield trends alongside national data sets for crop price, fertiliser or pesticide usage and other agronomic factors.
3. The use of farm specific data to investigate differences in, or changes to, agronomic practice that may be related to yield trends.
4. The examination of existing research evidence to quantify the likely yield impact of differences in, or changes to, agronomic practice.
5. An assessment of opportunities for, and barriers to, overcoming agronomic limitations to yield.

2.2. Materials and methods

Published reports were reviewed that have examined yield trends in countries around the world, and the contributions of genetic, climatic, economic and agronomic factors to these trends. Specific attention was given to recent studies from France and Denmark. The review findings were used to guide subsequent investigations of UK data. National and regional yield trends for oilseed rape and wheat were defined using data from Defra statistics, derived from cropped areas and production tonnages collected by the Cereal and Oilseed Rape Production Surveys. For wheat, investigations focused on the period from 1980 to 2011, either side of the apparent onset in 1996 of yield plateau. For oilseed rape, the double-low variety era from 1984 was considered most relevant.

Published analyses have used historical datasets for wheat and oilseed rape from UK National List (NL) and Recommended List (RL) trials to assess the potential contribution of genetic improvement to national yield trends. These analyses were reviewed and supplemented to enable the net impact of the growing environment to be determined. The effects of seasonal weather on year-to-year variation in national yields were analysed as single correlations and as multivariate analyses. The extent to which changing weather patterns may have influenced yield trends was also considered. Analyses focused on air temperatures, total rainfall, soil moisture deficit and sunshine hours.

NL and RL trials are conducted under defined conditions that often differ from typical farm practice. Improvements in the yield potential of new varieties evident within trials may not be fully expressed in farm situations, due to limitations in site conditions and management practices on farm. Recent yield trends for RL wheat trials were analysed to pinpoint similarities or differences that could help to explain farm yield trends. Crop selection and management practices may be influenced by fluctuations in crop prices and developments in agricultural policies. Prices were charted alongside yield trends, and price and policy effects were analysed by regression, to identify possible associations.

National survey data were accessed to evaluate changes in fertiliser and pesticide use. Sources included the annual British Survey of Fertiliser Practice and biennial Pesticide Usage Survey. As part of CropMonitor in England, annual disease surveys have been conducted in about 300 treated farm crops of winter wheat since 1975 and 100 crops of winter oilseed rape since 1987. Agronomic information has also been collected. Factors showing evidence of change over time were charted and compared to trends in national yields, with an estimate made of the potential qualitative or quantitative impact that could result from the extent of the changes observed.

Data from the Farm Business Survey in England were analysed for about 200 farms per year for wheat and 90 farms for oilseed rape from 2004 to 2009. They were used to identify differences in crop husbandry (as indicated by expenditure on inputs, labour and machinery) between farms in

the top and bottom yield quartiles, and associations between cropped area, yield and margin. To enable yields to be examined alongside agronomic data from the same farm, several case study farms were identified. Growers were asked about their cropping strategies and changes to their farming systems since the 1990s, and information collected on soil types, cropped area, variety choice, rotation, fertiliser inputs and establishment practices between 1996 and 2011.

A review of research results from controlled field experiments was undertaken to help quantify the potential contributions of key agronomic factors to yield change. These were scaled up to provide an estimate of the potential impact that the factor may have had on national average yield trends. Data sources included published research reports and reviews from HGCA, plus published or unpublished experiments by SAC or NIAB TAG that have investigated responses to various agronomic factors under commercially-realistic conditions in the main arable areas of the UK.

Opportunities for overcoming agronomic limitations, and barriers to their adoption, were assessed. Potential environmental impacts and implications for grain quality or end use were also considered. Recommendations have been made for knowledge transfer or research where information gaps need to be addressed. Consultation with practitioners was a key part of the project, including a stakeholder meeting that provided an opportunity to capture knowledge and experience, focus the study and interpret data. Further discussions helped to refine conclusions and recommendations.

2.2.1. Limitations

This initial study has examined the possible contribution of a wide range of agronomic factors to recent national yield trends, in the context of other potentially important influences. It has focused on farm yields and practices, rather than research trials. Yield potential using substantially-modified agronomic practices and technology-related yield gaps that might exist have not been considered.

The study was dependent on published and unpublished surveys, the accuracy of which is limited by the scale and sophistication of their sampling methodologies. Surveys have been limited by the level of detail requested, including lack of differentiation between winter and spring cropping. While wheat is known to have been dominated by winter cropping, proportions of winter and spring rape have been more variable. The impact of the lower yielding spring rape crop on the combined winter and spring national yield trend has been estimated in this report, but it was too speculative to try to relate changes in agronomic practice to just the estimated winter oilseed rape yield trend.

Weather data for the UK and England were available for the period studied. However, there has been no systematic collection of solar radiation and the use of sunshine hours as a surrogate has limitations. Examination of soil moisture deficit (SMD) data was also limited to specific locations. Testing of weather effects was limited to single and multiple correlations of yield with weather

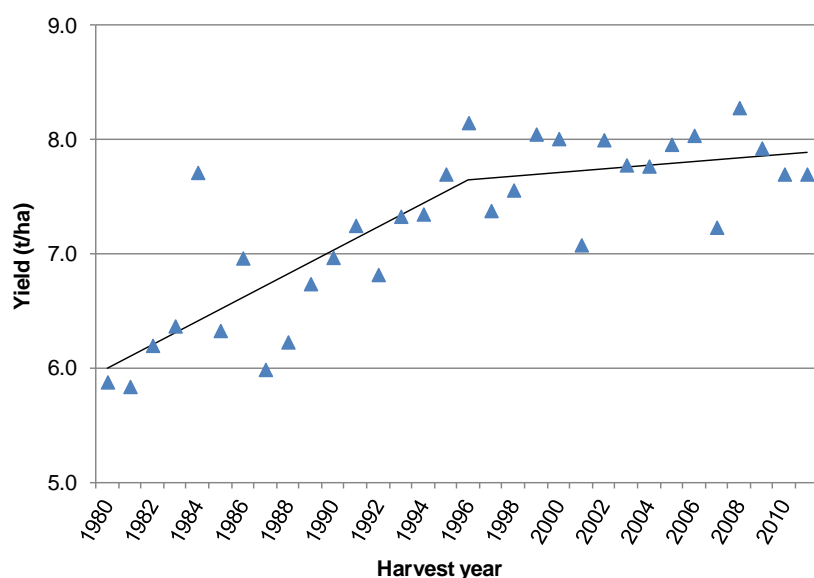
variables, and an examination of trends over time. This does not provide a proper assessment of the potential impact of climate trends on national yields, which could be explored through the use of a suitable crop model. However, this was considered to be outside of the scope of this study. There were a number of potentially important agronomic factors for which little or no data were available. These are highlighted in the report, and recommendations have been made as to additional data that should be collected in future. Together, they could account for a significant proportion of the unexplained yield effects over part or all of the time periods studied.

2.3. Results

2.3.1. Wheat

Yield trends

From 1980 to 1996 national average wheat yields increased by an average of 0.105 t/ha per year, but since 1996 the UK trend shows only a 0.016 t/ha per year rise (Summary Figure 1). Regional data since 1999 show that the trend for England (94% of the crop) is similar to the UK, whereas in Scotland yields continued to rise until the 2000s. Farm Business Survey data reveal a divergence in fortune for farms in different yield quartiles, with the gap between the top and bottom 25% rising from 3.0 t/ha in 1987 to 4.5 t/ha in 2009. Farms in the top yield quartile are growing twice the wheat area grown by farms in the bottom quartile, and are achieving the highest wheat gross margins.



Summary Figure 1. UK national average wheat yields from 1980 to 2011.

Genetics and yield potential

Previous estimates of the improvement in wheat yield potential due to genetics have ranged from 0.06 to 0.07 t/ha per year. A new analysis suggests that yields of the best nabim Group 4 varieties have increased by nearly 0.10 t/ha per year, whereas yields of varieties in Groups 1,2 and 3 have risen by about 0.04-0.06 t/ha per year, with an overall mean of 0.063 t/ha per year. Using certified

seed weights for the top varieties and lifetime average yields in trials, it is estimated that since 1990, apart from a slight dip from about 1996 to 2002, the potential for a yield increase of 0.05 t/ha per year has been maintained on farm through the effective uptake of new, higher-yielding varieties.

Climate and weather

Relationships between national wheat yields and monthly weather data for the UK or for England were examined for the 1980 to 2011 harvest years. Single variate analysis showed that a number of weather variables have contributed to yield variation. Multivariate analysis failed to contribute further to this picture. Rainfall for April showed a rising trend until 1996 but then a decreasing trend until 2011, with an increase since 1996 in April SMD. Sunshine hours for June show a rising trend, indicating the potential for increasing radiation during grain fill. High sunshine hours coincided with yield spikes in 1984 and 1996 and low hours with dips in 1987 and 2007. With rising temperatures, the trend in grain fill duration shows a decrease of about 3 days from 1980 to 2011. Heat stress during grain fill has been linked to yield stagnation in France, but since 1980 the incidence of June days above 25°C in England has been variable, with a weak rising trend for the last 10 days in June. While not explaining past yield stagnation, this may have implications for the future. An increase in atmospheric CO₂ concentration could equate to a yield increase of up to about 6% or 0.36 t/ha between 1980 and 2011, a contribution to yield improvement of about 0.011 t/ha per year.

Economics and policies

Wheat grain prices increased between 1980 and 1984, fell sharply from 1996 to 1998 and then remained flat before rising steeply but erratically from 2006 up to 2011. Regression analysis failed to show a significant short or medium term effect of changes in actual or inflation-adjusted prices on yield over the period as a whole. Nevertheless, the fall in prices between 1996 and 1998 that coincided with the start of yield stagnation was a likely driver for some of the changes seen in crop management since the late 1990s. The MacSharry proposals and set-aside seem to have had a positive impact on wheat yields, possibly due to removal of unproductive land from production.

Factors influencing recent yield trends in RL trials

The overall yield trend from 2002 to 2011 for varieties in their first year on the HGCA RL is shown in Summary Table 1. Different yield trends are apparent across RL climatic regions, with the wetter West and cooler North increasing more rapidly than for the same varieties in the dry East. Yield improvement is evident on heavier textured soils but there was almost no change on light soils. There was a consistent yield improvement in early sown RL crops, whilst late sown crops had high seasonal variation and no increase. These differences suggest a possible weather impact (notably spring or summer droughts) on the performance of wheat in at least some areas of the UK.

Summary Table 1. Yield trends in RL trials from 2002 - 2011, for varieties in their first year on the RL.

RL data set	Annual yield change (t/ha)	R ² of fitted line	se of regression coefficient	Significance <i>F</i>
Fungicide treated	0.040	0.382	0.0179	0.057
Dry East region	0.005	0.012	0.0174	0.764
Wet West region	0.025	0.124	0.0233	0.319
Cool North region	0.082	0.586	0.0243	0.010
Heavy textured soils	0.067	0.320	0.0347	0.088
Light textured soils	0.003	<0.001	0.0377	0.945
Early sowing	0.071	0.604	0.0217	0.014
First wheat	0.017	0.072	0.0210	0.452

Agronomy

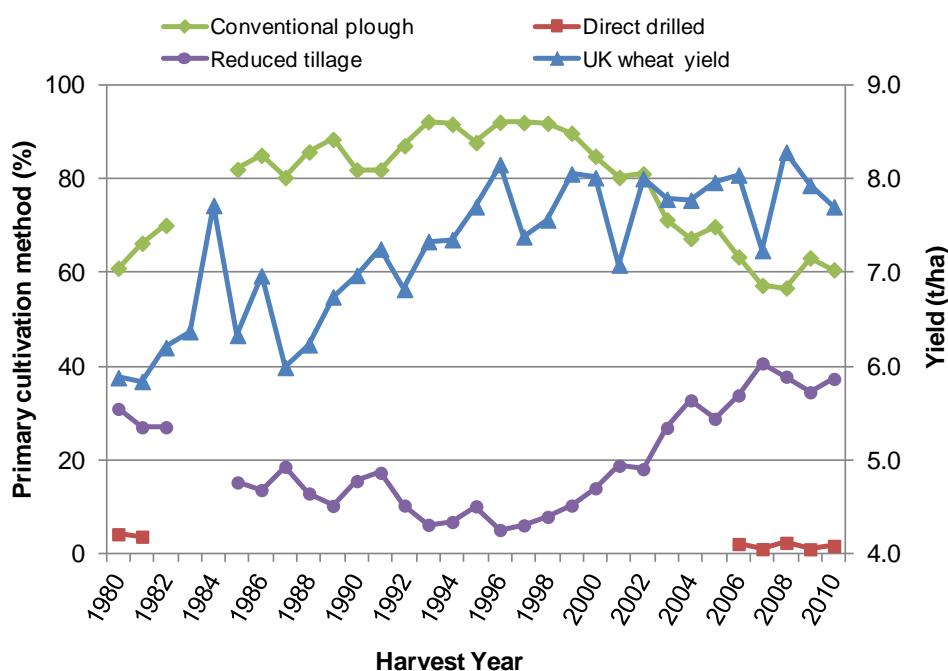
Average amounts of N fertiliser applied to wheat have been static since 1983. The optimum dose for modern varieties has risen by about 20 kg N/ha per tonne of yield improvement over varieties grown in the 1980s. However, the rise in break-even N to grain price ratio has negated this, which could be limiting yield by 0.12 t/ha, causing a yield decline of 0.006 t/ha per year. Grain %N values based on Cereal Quality Survey data also indicate that N use on wheat crops may be sub-optimal. Applications of phosphate (P) and potash (K) fertilisers have fallen by half since 1996. P and K budgets have been in deficit since the 1990s, but the proportion of fields tested with soil indices below critical is not rising. The crop area receiving S fertiliser rose in the 1990s but was insufficient to treat all crops at high risk of deficiency, lowering yields by up to 0.4 t/ha. The deficit was reduced from 1996 to 2002, with a likely contribution to yield improvement of up to 0.025 t/ha per year. This may be an over-estimate as not all crops treated would have been those at highest deficiency risk. There is little evidence to implicate trace element deficiencies as a cause of yield stagnation.

The severity of septoria leaf blotch infection in farm crops was generally higher between the late 1990s and early 2000s, coinciding with the pathogen developing resistance to strobilurin fungicides and a fall in fungicide doses applied. Yield loss is estimated to have increased by an average of 0.01 t/ha per year during that period. From 2002 to 2011 increasing fungicide doses and lower septoria pressure reversed this. Between the 1980s and 1990s the incidence of take-all fell from 15% to 5%, linked to a declining area of second wheat, with an estimated reduction in the national yield loss from 6% to 2%. Take-all incidence has since varied, with little indication of a rising trend.

There is little indication of rising pest incidence since 1996. Severity of attacks by orange blossom midge may have contributed to annual variation during the 1990s and early 2000s. The incidence of some nematode species may be increasing, but the implications of this for yield are uncertain. There is no evidence of an increase in rabbit damage that could be linked to yield stagnation.

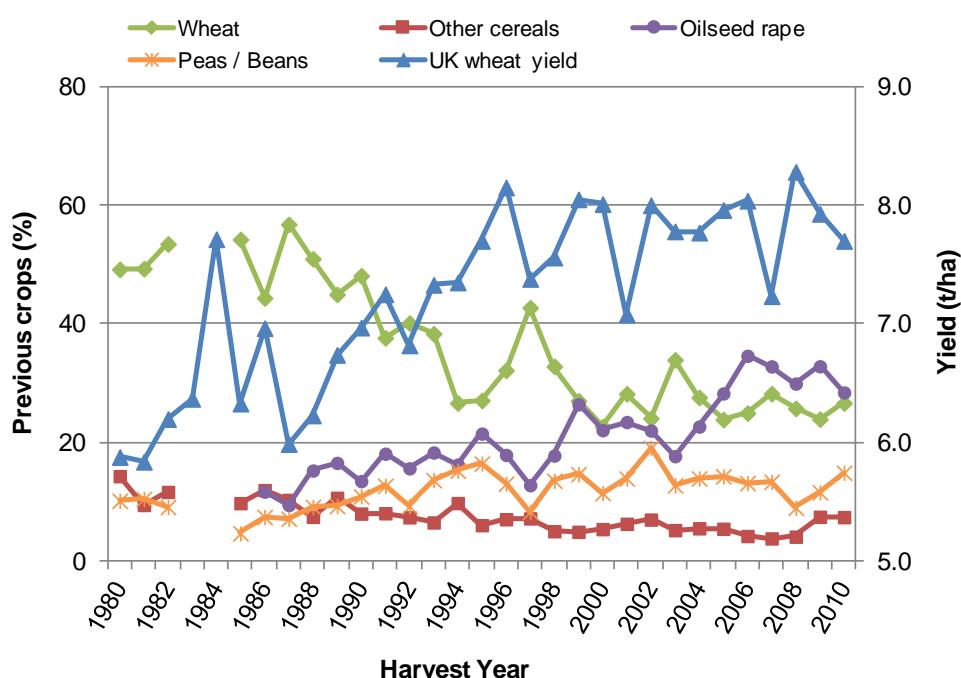
While there is little data to quantify changes in weed populations, it is widely known that control of grass weeds, in particular black-grass, is a concern in many key wheat producing areas. While the direct impact on yield may have been minimal due to a rise in the number of herbicides applied to maintain efficacy, there is an increasing number of farms where overall crop management strategies are influenced by the need to maximise black-grass control as well as optimising yield.

The proportion of wheat crops sown after ploughing rose from 60% to 90% from the 1980s to 1996 but had fallen back to 60% by the late 2000s (Summary Figure 2). Evidence for yield effects of minimum tillage over a long period is sparse, but estimates of wheat yield reduction have ranged from 0 to 4%. Two scenarios were considered for the period since 1996. Assuming a continuing 3% penalty from reduced tillage, a decline in yield about 0.007 t/ha per year is indicated. In an on-going study, a larger short-term yield penalty was observed during the transition from ploughing to non-inversion. This may be a year effect, but assuming a 12% penalty in the year of transition only, a yield decline of 0.004 t/ha per year is indicated. Machinery wheel loads have progressively increased, inducing high stresses in deep soil horizons irrespective of the tyres or tracks used. Soil compaction below sub-soiling depth may remain for a long time. UK research has indicated that soil compaction from trafficking can reduce cereal yields by an average of 16%, but there are no data to quantify the incidence and severity of compaction. In addition, up to 15% of under-drained land on cereal farms is potentially being mole drained less often than it should be. The mean organic matter content of arable soils declined from 3.3% in 1980 to 2.8% in 1995, but there is no evidence that this has been a direct cause of wheat yield stagnation.



Summary Figure 2. Establishment methods for winter wheat crops in England from 1980 to 2010.

The proportion of second or subsequent wheat crops declined from 50% in the 1980s to 30% in the 1990s (Summary Figure 3), due to an increase in wheat following peas / beans or oilseed rape. In a recent wheat and oilseed rape rotation study, the average yield penalties were 1.0 t/ha (10%) for second wheats and 1.4 t/ha (14%) for subsequent wheats. The decline in successive wheat crops could account for 0.015 t/ha per year of the rise in national wheat yields from 1980 to 1996. Since the 1990s, the proportion of wheat crops following oilseed rape has risen to 30%. The proportion of wheat after peas / beans has changed little, but there has been substitution of beans for peas. A five-year crop sequence study in England showed that wheat yields after peas were higher than after beans, which may have had a minor impact on yield trends. Wheat yields following oilseed rape were higher than following peas. In France, yields were found to be lower after oilseed rape than after peas, which could be explained by a lower amount of N being applied to oilseed rape.



Summary Figure 3. Proportion of crop types preceding winter wheat in England from 1980 to 2010.

The proportion of wheat crops sown before 1st October has increased from less than 20% in the 1980s to nearly 40% since the late 1990s. An analysis of NIAB TAG trials data over several sites and seasons compared yields of wheat varieties when sown in early-mid September, or from late October onwards, against the traditional late September / early October window. An average 1.4% yield advantage to 'early' sowing and 3.7% yield penalty to 'late' sowing were found. Advantages to September sowing have been variable in other studies. It is estimated that the trend towards earlier sowing could account for a national yield improvement of 0.003 t/ha per year since 1980. With conflicting results from field experiments and no data available to examine trends, the impact of farm seed rates on the national wheat yield trend is uncertain. However, target plant populations and seed rates advised in the early 2000s may have been sub-optimal for yield in some situations.

2.3.2. Key factors influencing wheat yield trend

Key factors that have contributed to the trend in UK average wheat yields from 1980 to 1996 and from 1996 to 2011 are shown in Summary Table 2. Some appear to have changed after 2002, so the latter period has been subdivided. Factors for which it has been possible to reliably estimate their effects do not account for all of the yield trend in either phase, with a proportion unexplained. In addition to weather patterns, a number of variables are highlighted as potentially having had an influence, especially during the 1996 to 2011 period, most notably deep soil compaction, but also of relevance are UV-B levels, soil pH, under-drainage, seed rates and timeliness and targeting of inputs and operations. Many of these are thought to have had a small negative impact on yields.

Summary Table 2. Factors contributing to the national wheat yield trend from 1980 to 2011.

Period	1980-1996	1996-2002	2002-2011
	Yield gain + or loss - with estimate of t/ha per year. 0 neutral, () uncertain		
Farm Yield	+0.105	+0.016	
Genetic potential	+0.05	+0.05	
Variety choice	0	-0.01	0
Agronomic effects			
Nutrition N	-0.006	-0.006	-0.006
Nutrition S	(-)	+0.025	0
Disease control	(+)	-0.01	+0.01
Rotation	+0.015	0	
Cultivation	+0.001 to +0.002	-0.004 to -0.007	
Sowing date	+0.003	+0.003	
Rising CO₂ levels	+0.011	+0.011	
Weather and/or other factors	+0.030 to +0.031	-0.040 to -0.043	-0.045 to -0.048

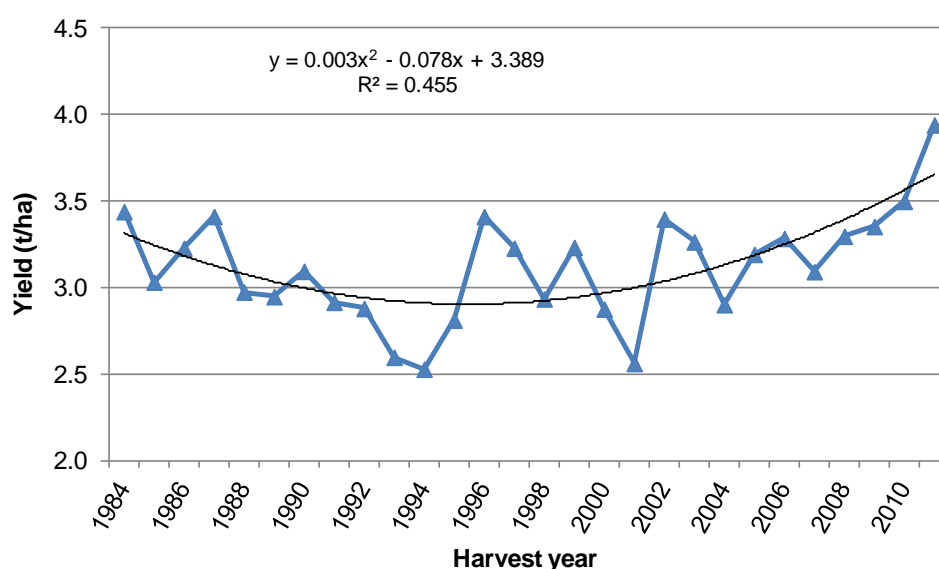
2.3.3. Oilseed rape

Yield trend

From 1984 to 1994 national oilseed rape yields fell by an average of 0.040 t/ha per year. Over the next ten years yields were highly variable, with an overall increase of 0.022 t/ha per year, but since 2004 yields have risen by an average of 0.075 t/ha per year (Summary Figure 4). Regional data from 1999 show that the trend for England reflects that of the UK, whereas yields in Scotland have maintained steadier improvement. A higher proportion of spring rape in the 1990s led to increased annual variation and reduced yield improvement. Farm Business Survey data from 1987 to 1999 show similar trends for the top and bottom yield quartiles, with a slight increase in the gap between them in the 1990s. No consistent relationship is evident between yield quartile and crop area.

Genetics and yield potential

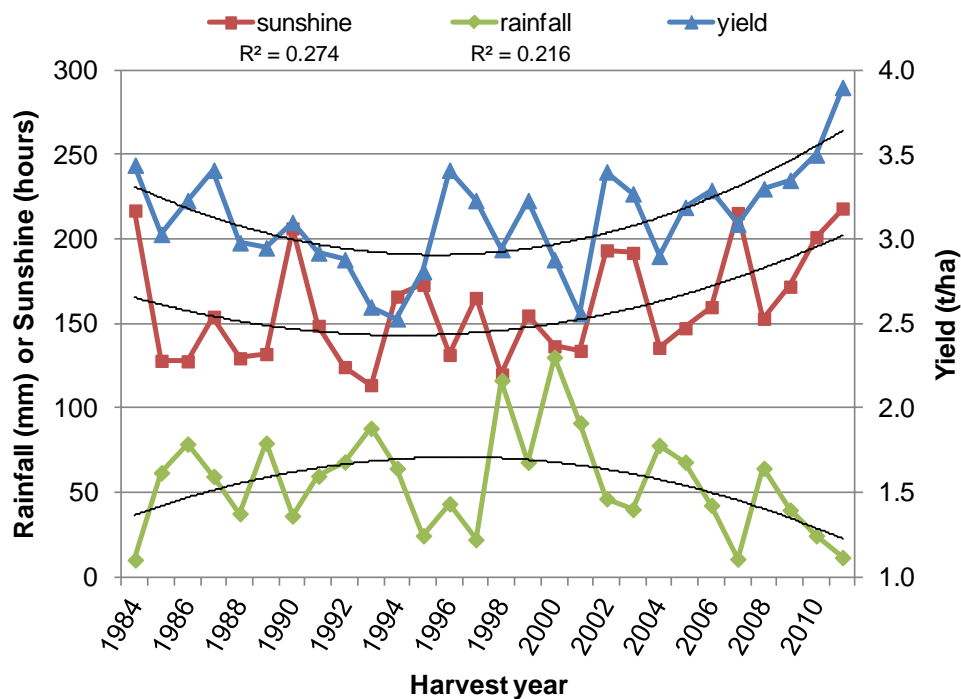
An updated analysis of NL and RL data shows that annual improvements in yield offered by the best new oilseed rape varieties are equivalent to 0.06 t/ha for conventional varieties and 0.05 t/ha for hybrids. These are similar to previous estimates, and equate to a potential yield gain on farm of about 0.048 t/ha per year. Although only one measure of variety selection on farm (as farm saved and imported seed account for part of the area), certified seed data indicate that prior to 2004 uptake of new high yielding varieties was poor due to growers selecting varieties that were easier to manage and harvest. This led to a widening gap in theoretical yield potential between that of the best varieties available and that of the variety set being grown. This is estimated to have reduced yield gain on farm from genetic improvement by more than half. Since 2004 better uptake of new varieties has started to close this gap, with a small positive contribution to yield improvement.



Summary Figure 4. UK national average oilseed rape yield trend in the double-low era (1984 to 2011).

Climate and weather

Relationships between UK oilseed rape yields and monthly weather data for England and for the UK as a whole were analysed from 1984 to 2011. Single variate analysis indicated that several weather variables have contributed to yield variation. Multivariate analysis did not add to this. Yield responded positively to increasing sunshine hours and negatively to increasing rainfall in April, with trends over time in yield and sunshine remarkably similar (Summary Figure 5). The most likely explanation for this is improved seed-set, resulting from enhanced pollination or increased crop photosynthesis. Higher yields have also been associated with cold, dry, sunny December weather, probably due to a suppressing effect on some pests and diseases (phoma, but not light leaf spot).



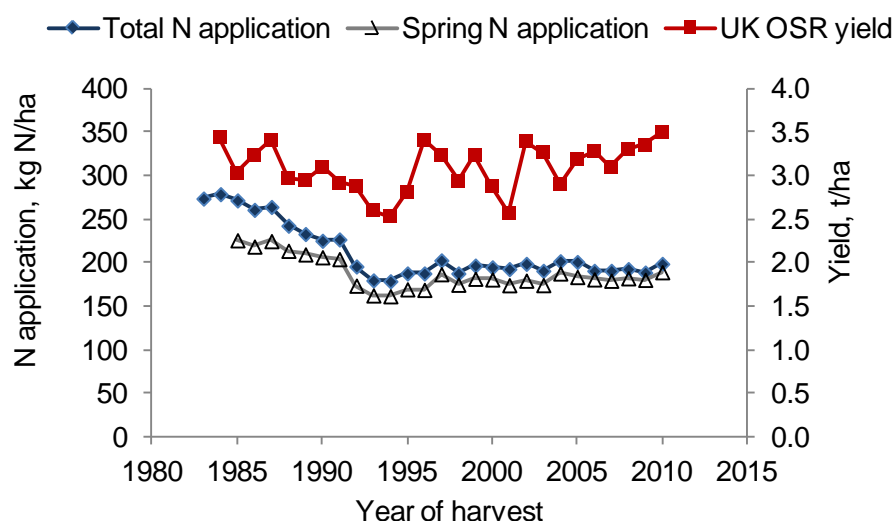
Summary Figure 5. Trends for UK oilseed rape yield and April rainfall and sunshine for England.

Economics and policies

Oilseed rape prices fell sharply after 1991 and between 1996 and 1999, before rising rapidly from 2006 to 2011. Regression analysis failed to indicate a significant short- or medium-term impact of crop price change on oilseed rape yields. A subsequent analysis showed that for the period from 1984 to 1994, characterised by falling prices and declining yield, crop price and yield were highly correlated ($r = 0.767$, $p < 0.01$). After 2000 rising prices again saw a relationship between crop price and yield ($r = 0.661$, $p < 0.05$). The spike in the area of spring oilseed rape grown in the mid-1990s partly resulted from the introduction of area payments, which made the lower inputs of spring rape more attractive, despite a lower yield potential, once this was offset by the crop subsidy.

Agronomy

The average amount of fertiliser N applied to oilseed rape fell from about 270 kg N/ha in 1983 to 179 kg/ha in 1994 (Summary Figure 6). A reduction in autumn N use explains 30% of this, but the decline in spring N dose accounts for an estimated yield drop of 0.20 t/ha. It is uncertain if the N requirement of modern varieties has risen with yield potential, but a NIAB TAG survey has hinted that current amounts of spring N (180-190 kg N/ha) are sub-optimal. P and K applications have fallen since the 1980s but net budgets have only been in deficit since the 2000s. The proportion of crops treated with S fertiliser increased from 5% in 1993 to 60-70% by 2003. S deficiency may have limited national yields by up to 0.4 t/ha in the early 1990s. By the early 2000s the estimated yield penalty had fallen to about 0.1 t/ha, a contribution to yield improvement of about 0.027 t/ha per year, assuming that the fields being treated were those at highest risk of deficiency. There is no evidence to link changes in trace element status of oilseed rape crops to observed yield trends.



Summary Figure 6. Trends in the amount of N applied in total and in spring to oilseed rape in Britain.

The proportion of crops treated with a fungicide in autumn increased from the mid-1990s to 2000s. During this period, crop survey data indicate a higher incidence of phoma leaf spot in the autumn but a fall in light leaf spot incidence in the spring. Since then autumn fungicide use has remained high, and average levels of phoma leaf spot and stem canker have fallen, but the incidence of light leaf spot has risen. By 2002 use of fungicides at flowering had fallen to half of its 1994 level. This trend was reversed from 2004 due to sclerotinia concerns, improving prices and availability of new fungicides. With substantial variation, opposing disease trends and gaps in survey data it is not possible to reliably estimate the overall impact of disease on the national yield trend, but it is thought to have accounted for a small net yield decline from 1984 to 1994 and a small net yield improvement from 2004. Yield impacts over time of verticillium wilt and clubroot are also unknown.

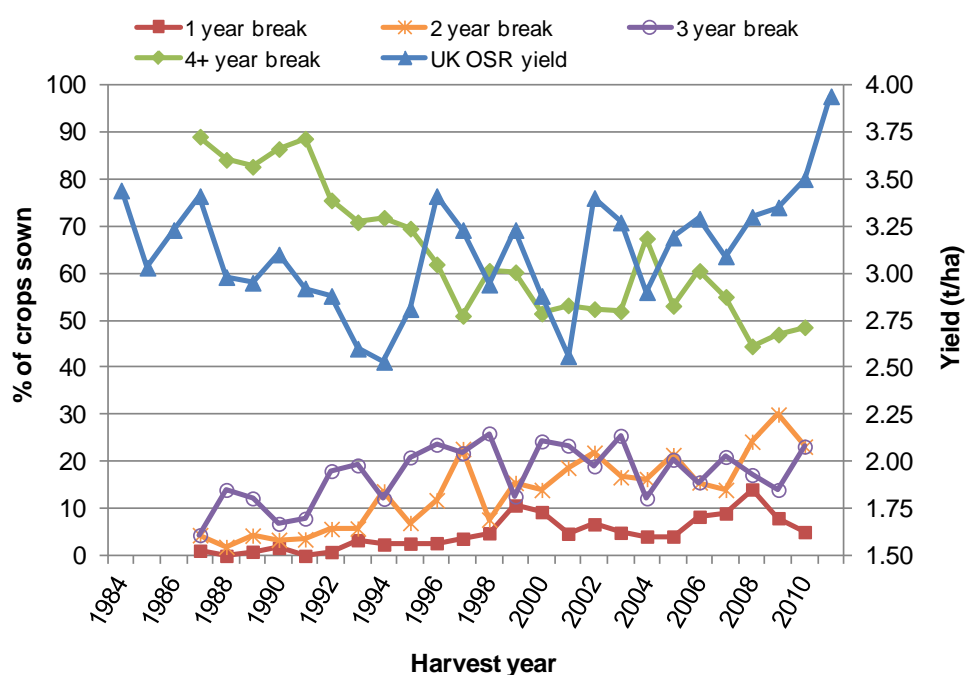
With potential to reduce yields by up to 26%, the effects of Turnip Yellow Virus (TuYV) may have had an impact on the national trend for oilseed rape. The annual occurrence of aphids causing TuYV is variable, but there is little evidence to suggest an increase. From 1987 to 1997, autumn insecticide use increased erratically from less than 10% of crops treated to around 70%. From the 1990s to mid-2000s there were similarities in the patterns of annual insecticide use and national yield. The increasing use of insecticidal seed treatments since 2002 may have diminished this.

Survey data indicate that from 1988 to 2006 the number of pollen beetles in farm crops averaged below 5 per plant in nearly all years. There is no indication of a rising trend in beetle numbers over that period, but despite this an increasing proportion of crops have received an insecticide spray at flowering since 2002. Although pollen beetle damage will account for some yield loss in some crops, if anything, this is likely to have decreased. Wood pigeon numbers have nearly trebled since the mid-1970s, but the level of impact on national oilseed rape yields is not known.

Only two weed species, chickweed and black-grass, are estimated to cause annual yield losses of 0.5% or more with current herbicide treatments. Survey data show a rising number of herbicide applications, and a doubling of the number of active ingredients applied, from 1998 to 2008. Although black-grass has become more difficult to control, it is unlikely that this would have had a significant direct impact on national yields. Other management changes aimed at maintaining or improving grass weed control may have had an incidental effect. Farm Business Survey data show that farms in the top quartile for yield are spending more per hectare on pesticides than farms in the bottom quartile. The gap between top and bottom has increased from 15% in 2004/05 to 25% in 2008/09. Expenditure on pesticides was less for oilseed rape than for wheat in 2004/05, but is similar in 2008/09, suggesting that investment in oilseed rape has increased more than in wheat.

Although comparisons are limited by a lack of UK data, reduced tillage may have had more impact on oilseed rape than on wheat. Average yield reductions relative to ploughing of 9% and 5% have been recorded for shallow and deep non-inversion respectively in one experiment, but these have not been consistent. On farm there was an initial shift from ploughing to autocasting or shallow non-inversion; although saving cost, conserving moisture and potentially improving black-grass control, it is likely that this had a detrimental effect on yields. More recently, deep tine systems that give a greater degree of spoil loosening have become common, along with direct drilling. The net yield impact is unclear. Although it cannot be quantified with certainty, the shift to non-inversion is estimated to have reduced overall yield improvement by 0.006 t/ha per year from 1994 to 2010.

Survey data highlight a decrease in the proportion of oilseed rape crops sown after a break of 4 or more years, with a rise in crops sown after a break of 2 or 3 years (Summary Figure 7). Data from a recent 8-year field experiment in the UK, in which a range of crop sequences involving oilseed rape and wheat were evaluated, have led to yield loss estimates of 3%, 6%, and 12% for oilseed rape crops with a break of 3 years, 2 years or 1 year respectively, compared to a break of 4 or more years. These could underestimate the yield loss for short rotations maintained over a longer period. The resulting reduction in national yields is estimated to have risen by 0.004 t/ha per year.



Summary Figure 7. Proportion of oilseed rape crops in England sown after a 1, 2, 3 or 4+ year break.

2.3.4. Key factors influencing oilseed rape yield trend

Key factors that have contributed to the UK oilseed rape yield trend from 1984 to 2011 are shown in Summary Table 3. They are split into three phases, defined by falling yields until 1994, variable yields from 1994 to 2004 and rising yields since 2004. Yield potential has continued to benefit from genetic improvement, but from 1984 to 2004 poor uptake of high-yielding varieties that were less attractive to grow meant that on farm over half of this was not being deployed. Factors for which it has been possible to reliably estimate their effects account for most but not all of the trends in yield in each phase. In addition to weather patterns, a number of variables are highlighted as potentially having had an influence. From 1984 to 1994, increased varietal susceptibility to lodging, rising numbers of pigeons and relatively high levels of TuYV may have contributed to the remaining yield decline of 0.027 t/ha per year. From 2004 factors that may have contributed positively include increased use of insecticidal seed treatments and the effects of lower seed rates and fungicides with growth regulatory activity on management of the crop canopy and lodging control. The overall positive impact of these may be larger than the 0.015 t/ha per year indicated, as at the same time factors such as soil compaction and soil-borne diseases may have had a negative effect on yields.

Summary Table 3. Factors contributing to the national oilseed rape yield trend from 1984 to 2011.

Period	1984-1994	1994-2004	2004-2011
Yield gain + or loss - with estimate of t/ha per year. 0 neutral, () uncertain			
Farm Yield	-0.040	+0.022	+0.075
Genetic potential	+0.048	+0.048	+0.048
Variety choice	-0.031	-0.038	+0.014
Spring OSR area	-0.009	-0.003	+0.008
Agronomic effects			
Nutrition N	-0.02	0	0
Nutrition S	(-)	+0.027	0
Crop Protection	(-)	0	(+)
Rotation	-0.004	-0.004	
Cultivation	+0.003	-0.006	
Weather and/or other factors	-0.027	-0.002	+0.015

2.3.5. Opportunities for overcoming agronomic limitations to yield

Variety selection

The Recommended Lists provide robust, comparative information on the yield potential of varieties and their agronomic characteristics. But the challenge facing growers is to select varieties that are appropriate for their farm and to optimise their management. More information (site characteristics, local environment or farming system) is needed to help match varieties to specific farm situations, to demonstrate how varieties that offer a step forward in yield can be grown profitably on farm.

Nutrient supply

To respond to higher yield potential and support rising yield trends, the extent to which N supply limits current yields of oilseed rape and wheat must be reduced. There is likely to be a case for increasing the amounts of N fertiliser applied to some crops but, with economic and environmental constraints to consider, part of the answer must be to focus on N use efficiency. Plant breeding and fertiliser technology are important but agronomy also has a role to play by creating conditions that will maximise N uptake by the crop. For S nutrition, more could be done to ensure that all crops at risk of deficiency, or likely to give a yield response, are identified and receive S fertiliser.

Rotations

The increase in break crops and decrease in successive wheats contributed significantly to wheat yield improvement prior to 1996. However, there is evidence that the rise in oilseed rape cropping frequency is limiting oilseed rape yields. About half of the English oilseed rape crop is grown with a break of four or more years. If this proportion declines further, and the incidence of soil borne threats increases, the yield effects could be significant, especially on large farms growing wheat

and oilseed rape only. Efforts must continue to address these threats, and wider rotations may form part of the solution. It is recognised that most rotations will continue to be driven by overall profitability rather than the yield potential of individual crops.

Crop protection

Crop protection metrics indicate no reduction in robustness over the last 30 years. Breeders have improved pest and disease resistance, uptake of new chemistry has been good, and numbers of active ingredients applied and application rounds have risen. There is little evidence that a general increase in pesticide use is needed to remove yield restrictions, although inadequate control of weeds, pests or diseases will still limit yields in challenging seasons and situations. Efforts should be focused on the threat posed by pathogen evolution, pesticide resistance and a likely decline in number of modes of action to our ability to sustain rising yields in future. Good agronomy relies on a combination of chemical and cultural control measures. Although well publicised for weeds and diseases, this may become more important for insect pests and nematodes. More should be done to evaluate and demonstrate the benefits of combining chemical and non-chemical control.

Sowing date

Earlier sowing of wheat is potentially a key measure to reduce the impact of weather-related yield limitations, notably to lessen the effects of spring / summer droughts that have occurred in several recent seasons. Wheat sowing dates have been advancing over the last 3 decades. Trials indicate this has contributed positively to the national yield trend. Early sowing is not without problems, such as lodging, grass weeds and elevated pest and disease threats. Some could be overcome by adjusting crop protection strategies but, even so, it will not be the right strategy for every grower to improve yield and won't be of benefit in every year. Lighter soils most at risk from drought are less affected by black-grass and are the main target for earlier sowing. Changes to rotations may be needed to avoid late sowing, following late-harvested root crops with a spring crop instead of winter wheat. This particularly applies where soil conditions are poor, as it risks compounding drought risk with compaction, although spring crops themselves can be compromised by drought.

Soil management and cultivations

Soil management may have suffered through change being driven by what is technically possible and economically attractive rather than agronomically appropriate. New cultivation equipment and drills have saved time and fuel, and delivered effective establishment. However, the industry has been on a learning curve, during which yields may have suffered in the short term. There has been little emphasis on soil management studies, undertaken and interpreted in the context of today's production systems. The trend towards heavier machinery is a particular concern. The extent and impact of soil compaction at or below sub-soiling depth needs to be quantified, along with the state of UK soils in terms of other measures such as under-drainage and organic matter content.

Management intensity

As fields and farms have increased in size, and growers have sought to simplify their management through block cropping, there is a risk that the husbandry applied to individual fields may become less well matched to their specific needs. However, Farm Business Survey data indicate that yield improvement is not necessarily compromised on farms that are growing a larger area of a crop, and that this may in part be due to greater investment in labour and machinery. 'Attention to detail', 'getting everything right' and 'continuing improvement' were articulated by practitioners as vital to achieving positive yield trends on individual farms. Approaches to this have included:

- Involvement in grower groups that seek out and share knowledge;
- Engaging the whole farm team in understanding crop performance;
- Investment in training, more effective machinery or technology to capture / analyse information;
- Making more use of agronomists or specialist advisors to help improve the farming system.

A number of precision farming techniques also have the potential to help deliver better targeting of agronomy, facilitating attention to detail while improving the outputs from labour and machinery.

2.3.6. Barriers to overcoming agronomic limitations to yield

Environmental constraints and tensions

Although soil processes that influence greenhouse gas (GHG) emissions are recognised, less is known about the relative contribution of crop management factors. Emissions are most likely to be reduced by a combination of increased crop N use efficiency and the avoidance of husbandry practices associated with significant nitrous oxide (N₂O) losses. Emissions of N₂O and carbon dioxide (CO₂) from soils are highly variable. Both soil management and crop species influence N₂O emissions. The overall impact of min-till or no-till on emissions needs to be considered in relation to soil type and structure. Under min-till systems the emission of CO₂ from fuel usage is reduced. Fuel consumption under no-till is invariably less than under ploughing, though the difference will depend on the soil type, the depth of cultivation and the requirement for secondary cultivations.

Earlier sown wheat crops should on average have a larger biomass going into the winter, and will have taken up slightly more residual N from the soil (though this effect is much greater with oilseed rape). As a consequence there may be a small reduction in leaching risk, especially on lighter soils for which earlier drilling is of greater benefit. It is likely that earlier sowing and the potential for larger crop canopies or earlier closure would reduce growth of spring-germinating weed species, which may have a negative effect on the diversity of arable plants and associated invertebrates, and reduce feed and access for ground-foraging or ground-nesting birds. This probable tension

requires further specific consideration. In addition, the likely increase in pest and disease risk may have implications for autumn pesticide usage (notably seed treatments).

Legislative constraints

Regulations for Nitrate Vulnerable Zones (NVZs) establish a limit on the amount of N that can be applied to crops. Current limits for wheat and oilseed rape allow for additional N to be applied where expected yields exceed the standards assumed (8.0 t/ha and 3.5 t/ha respectively). If it can be shown that yield potential is higher, current regulations should not be a barrier to increasing N supply to support higher yields. However, any reduction in limits could constrain yields in future. A number of important pesticides have been lost in recent years, or are under threat, as a result of changing European legislation. The Water Framework Directive, Drinking Water Directive, Sustainable Use Directive and the adoption of hazard-based criteria for approvals may have implications for pesticide use in significant areas of the UK. Withdrawal of pesticides not only reduces opportunities to control pests, weeds or diseases but places extra pressure on those that remain available. In some cases this may increase their chance or level of detection in water or the risk of resistance development through over-dependence on the same mode of action for control. An integrated approach to crop protection regulation is essential to maintain yield improvement, including timely approval of new active ingredients to replace the loss of existing ones.

Uptake of technologies

On the whole, the application of technological developments does not appear to have been much of a constraint. However, the ability to exploit genetic potential at a whole field or farm level, rather than simply at the small plot scale at which progress is currently assessed, appears to be a barrier. Trial yields may be achieved at a relatively high input level and cost, which if transferred to farms may incur additional or undesirable environmental or economic costs. The extent to which, in the future, new plant breeding technologies, including genetic modification, might aid the realisation of improved yield potential on farm through novel solutions to current limitations could be important.

2.3.7. Quality and end use considerations

For wheat and oilseed rape a case has been made for increasing the supply of N and potentially the area receiving S. Increasing N dose or S application should not reduce feed wheat grain quality, and for breadmaking may improve the chance of meeting the required specification. High starch and low protein grain is preferred for bioethanol, so avoiding overuse of N may become vital as it accounts for about 70% of the GHG emissions from wheat production. For oilseed rape the % oil content of the seed decreases with increasing N dose but oil yield and gross output are still improved. Increasing N may also have an adverse effect on oil quality through an increase in seed chlorophyll concentration in some circumstances. In contrast applying S on a deficient site can increase % oil content and lead to an overall decrease in seed chlorophyll concentration. A small

increase in glucosinolate content may occur with higher N doses or S application but this is unlikely to be sufficiently large to affect suitability of the meal for inclusion in non-ruminant livestock rations.

2.4. Conclusions and recommendations

No single agronomic factor has had a clear dominant influence on trends in UK wheat or oilseed rape yields over the last 30 years. A proportion of the lost yield improvement remains unexplained, with aspects of climate change being amongst the likely causes. Plant breeding has continued to deliver genetic improvement in both crops, but until recently uptake of higher-yielding oilseed rape varieties on farm was relatively poor. Weather patterns have had an impact, but appear to have acted in varying and opposite directions for wheat and oilseed rape. Apart from 1980 to 1996 in wheat, alterations to agronomic practices have had a number of mainly small effects. Some of these have been driven by prices or policies, with growers seeking to maximise profit rather than yield. To restore rising yields in the face of warmer conditions, potentially more extreme weather, economic or environmental pressures and evolving weed, pest or disease threats, there is a need for some changes to farming systems, with a longer-term and more holistic approach to agronomy.

2.4.1. Short term: getting the most from current technology

Short-term opportunities to raise farm yields involve additional knowledge transfer to address apparent shortcomings in agronomic practice. Not all growers will benefit, as many will already be employing best practice, but they may provide quick wins for others to improve crop performance.

1. Building on 'RL Plus', the outputs of the RL variety evaluation system should be supplemented by additional information, including potential interactions with soil conditions, fertility, rotation, crop environment and local climate, to guide variety selection for specific situations, recognising that limitations to performance may differ under challenging and varied farm conditions. This is both a knowledge transfer need and a gap in the current variety evaluation system.

2. Achievement of higher farm yields may require a less conservative approach to variety selection and management. Ease of harvesting and avoidance of lodging are understandable reasons why growers may reject higher-yielding varieties or hold back on seed rate and N use. Better tools and information to aid forecasting, monitoring and management of growth and lodging risk are needed, for example the use of canopy sensing technologies to target PGR treatments.

3. Various HGCA projects have studied aspects of crop husbandry that are relevant to early sown wheat crops. Key messages from these should be reviewed and brought together in a suitable format to inform best practice for the management of early sown wheat crops.

4. The proportion of wheat and oilseed rape crops currently treated with inorganic S fertilisers (40% and 60% respectively) equates to little more than that at high risk of deficiency. Although some will be receiving S in other forms e.g. organic manures, there is likely to be an area of crop, especially oilseed rape, at medium risk that isn't being treated. Updated advice on areas of the UK in which crops are at medium or high risk, and likely to respond to treatment, should be made available.

5. About 20% of soil samples tested are below the target P index for arable cropping, with 30% below the target K index. Although there is no evidence that this has contributed to yield stagnation or that the proportion of sites below target is increasing, with negative net budgets for P and K and off-take proportional to yield, there is a risk that this may change. Current soil testing technology should be checked for its effectiveness in modern arable conditions and further knowledge transfer is needed to reaffirm the benefits of regular soil testing, to ensure effective targeting of fertilisers to fields where yield is at risk, and to avoid low P or K indices becoming a yield limitation in future.

6. This study has highlighted the consequences of responding too late to pesticide resistance. In the case of septoria in the late 1990s, fungicide doses declined on the back of low crop prices and more expensive new fungicides, with little priority given to managing risk or robustness of control. With fungicide sensitivity a continuing issue for septoria and light leaf spot, the on-going problem of resistant black-grass and emerging problems of resistant aphids and pollen beetles, it is essential to maximise awareness of risks and practical implications, especially how to manage resistance through changes to control strategy and the integration of chemical and cultural control measures.

7. While not always within a grower's control, timeliness is undoubtedly pivotal in the effectiveness of certain operations and inputs. Agronomy information tends to focus on comparison of products, doses or techniques, but the implications of mistiming for yield should be made equally accessible.

2.4.2. Short to medium term: areas of uncertainty

A number of factors have been identified that may be having a negative impact on national yields, but for which information is lacking on their incidence or importance. Many are being investigated but more could be done to raise awareness or widen engagement in addressing the problem.

1. The extent to which changes in weather patterns / climate have contributed to yield trends in wheat and oilseed rape over the last 3 decades requires a dedicated investigation and analysis, including the use of suitable crop models, which was outside the scope of this study.

2. Reducing the extent to which N supply limits current yields of oilseed rape and wheat is vital to support a rising yield trend, but applying more N fertiliser is not sustainable because pollution risks and GHG emissions may increase even if efficiency of use could be maintained. Further studies

are needed to show how fertiliser technology or agronomy can impact on or improve fertiliser efficiency, including interactions with soil management and rooting.

3. It is unclear whether or not plant breeding has led to increased N use efficiency in modern oilseed rape varieties, or if they require more N. The extent to which current fertiliser N doses and timing are sufficient to realise the yield potential of varieties being grown needs to be clarified.

4. There is a need to raise awareness and further evaluate the contribution of pollination to yield in oilseed rape. Operation Pollinator (<http://www.operationpollinator.com/>) is addressing this, but the extent to which this is a determinant of oilseed rape yields may be underrated. There is a potential 'win-win' by addressing the challenge of simultaneously raising productivity and environmental benefits, which could be achieved practically through greater use of pollen & nectar margins combined with crop management that takes more account of the value of insect pollination.

5. There is a critical knowledge gap with regard to the state and health of UK soils and implications for yield, including the incidence and severity of compaction at and below sub-soiling depth, the maintenance of under-drainage systems and variation or trends in soil organic matter levels.

6. Further evaluation of the incidence (location/season) of nematodes in wheat and oilseed rape is needed to understand their potential impact on crop performance, including the effects of weather, soil type, rotations and cultivations, and the implications for variety selection or plant breeding.

7. Further evaluation of short- and long-term yield implications for wheat and oilseed rape of the move from ploughing to non-inversion cultivation is needed. A recent study has indicated that penalties may be associated with the initial transition but it is unclear if this is just a first year affect, an unavoidable consequence or due to poor management of the transition phase. It could have particular importance for farms that use rotational ploughing as part of a cultural control strategy for grass weeds. New HGCA-funded projects on soil management may help to address this.

8. There appears to be little independent information on the extent of secondary (Mg) or trace element (Mn, B, Mo) deficiencies in oilseed rape, or on likely yield responses to their application. A full review of existing knowledge, and new data from field experiments to fill any gaps, are needed.

2.4.3. Medium term: changing approach

Constraints to yield improvement have altered over time, often as a consequence of changes to cropping in response to prices or policies rather than for agronomic reasons. In some cases there may have been a price to pay in the long term for profitability in the short term. A new approach is

needed for assessing and improving the longer-term performance, output and resilience of farming systems, while maintaining flexibility to respond quickly to emerging threats and new solutions.

1. Farm Business Survey data has highlighted the divergence in yield trends between farms in the top and bottom yield quartiles. Farm benchmarking is justifiably focused on financial performance, but more could be made of the data gathered in understanding differences between farms in their yield or yield trends. This could provide useful indicators of potential limiting or derestricting factors.
2. Information, tools and advice are needed to help growers 'health check' their farming system and to encourage a longer-term approach to cropping and crop management strategy. This goes beyond conventional benchmarking and includes the likely impacts of rotation, cultivation and soil management strategy on current and future yield potential, productivity and the vulnerabilities or robustness of the farming system.
3. Precision farming techniques and technologies have the potential to improve the timeliness and targeting of inputs or operations, and to help maintain attention to detail as farms get larger. However, they also need to be more practical and accessible for small or medium-sized farms.

2.4.4. Long term: preparing for the future

This study has focused primarily on looking back in order to identify some of the factors that have contributed to the failure of farm wheat and oilseed rape yields to show consistent improvement. It is vital that there is also now a focus on future yield potential, from genetic, climatic and agronomic perspectives, so that the industry is better prepared.

1. Data on farm practice, from national statistics or surveys such as CropMonitor, are invaluable as indicators of change. But there is information that is not being collected that would be useful, and other data lacks sufficient definition to fully characterise change. This would include variety choice and establishment method for oilseed rape, more precise information on cultivation type and depth for wheat, seed rates, weed incidence and a more universal survey of soil and crop nutrient status. This is vital for monitoring shifts in practice, to help anticipate effects or constraints on crop performance.
2. Although this study did not examine the specific impact of changing climate, there is evidence in both wheat and oilseed rape of positive and negative impacts from higher temperatures and drier springs. These have been linked to wheat yield stagnation in Europe, and are a potential threat to our ability to raise UK yields in future. Breeding and selection of varieties suited to changing and varying environmental conditions around the UK remain an important priority.

3. TECHNICAL DETAIL

3.1. Introduction

3.1.1. Background

Estimates of UK wheat areas are available from 1866 (Figure 1). By 1874 the national crop had risen to just below 1.5 M hectares but declined after this point as the country became increasingly reliant on imports of agricultural commodities. Though continuing to show considerable variation, the area settled down in the 0.5 to 1.0 M hectares range for the first half of the twentieth century, showing brief spikes of additional production during the two world wars. After 1945 a general increase to around 0.75 M hectares was observed. Not until the early 1970s, with the combined influences of the UK joining the Common Market and increasing commodity prices, did the national crop exceed 1 M hectares and begin to climb rapidly to the current area of about 2.0 M hectares.

UK average farm yield estimates for wheat (winter plus spring) are available from 1885 onwards (<http://www.defra.gov.uk/statistics/foodfarm/food/cereals/cerealsoilseed/>). The yield data are characterised by marked annual variations and a number of phases of yield improvement (Figure 1). In 1885 the national yield average was recorded as 2.4 t/ha and by 1948 this had only risen to 2.8 t/ha, with the average for this whole 63 year period also being 2.4t /ha, but showing typical annual variations of 0.3 - 0.5 t/ha.

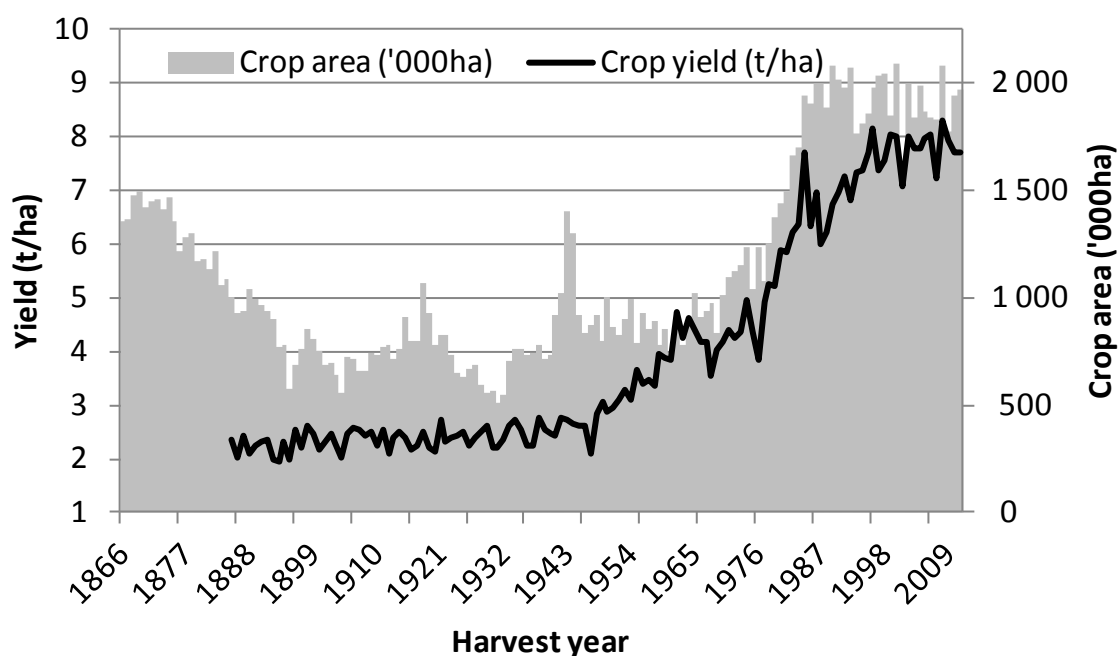


Figure 1. UK national average wheat yield and production area from 1885 to 2011

The 50 year period following the Second World War saw exceptional growth in the yield of wheat. Spurred on by the desire to be more self-sufficient, a combination of improvements to farming

methods, plant breeding and agronomy saw wheat yields reach the 3 t/ha mark for the first time in 1949, rising to 4.7 t/ha by 1962. A period of apparent yield stagnation and increasingly erratic annual variation followed until the mid to late 1970s, when a further period of very rapid yield improvement took effect, peaking at 7.7 t/ha in 1984. This production level was not maintained and dipped to 6.0 t/ha in 1987 before increasing again to 8.2 t/ha in 1996. Nevertheless, this represented the equivalent of an increase of 0.1 t/ha per year or 1 t/ha per decade over a 50 year period. Since the mid-1990s, national average wheat yields appear to have stalled, with significant annual fluctuations between 7.0 and 8.0 t/ha but no obvious increasing trend, culminating in successive year means of 7.7 t/ha for 2010 and 2011.

Oilseed rape, grown as both oil and forage crops, has been known in Britain since Roman times and there are records of oil mills in Lincolnshire in the 17th century. Converted yield records from the 19th century characterise the crop in the 1.8 to 2.5 t/ha range. In the 20th century cultivation of oilseed rape expanded in Europe, particularly Germany, France, Poland and Sweden but was not recorded in the UK by the FAO survey for 1948-52, which put total European production at 720,000 tonnes. In the 1960s there was renewed domestic interest in oilseed rape as a non-cereal break crop and production reached 15,000 tonnes in 1967 but fell back again to 8,000 tonnes in 1970. At this time the majority of varieties were relatively low-yielding spring types. After 1970 oilseed rape began a steady crop area expansion in the UK, encouraged by increasing commodity prices and elements of the Common Agricultural Policy (CAP), which provided price support for oil and protein crops in order to promote an improved level of self-sufficiency. A series of economic and policy drivers have continued to act upon the crop, encouraging its expansion to present day levels.

Systematic UK oilseed rape crop area and seed yield data have been recorded from 1970 onwards (Figure 2). The area of crop has now expanded to 700,000ha, but the varying proportions of spring and winter cropping have not been routinely recorded. While the majority of the crop has been autumn-sown, spring sowing is known to have been significant in the early days of oilseed rape growing up until the late 1970s, accounting for the low yields observed during these periods. Since the crop moved to mainly autumn sown varieties in the late 1970s, average yields have fluctuated around 3 t/ha, only starting to show a consistent trend of improvement in the last few years.

The overall shape of the yield trend indicated for oilseed rape to a large extent depends on the period of time considered. This study identifies several phases, including rising yields with the move from mainly spring varieties to 'single-low' winter varieties in the 1970s, a period of decline following the introduction of 'double-low' varieties in the mid-1980s and a period of very variable yield performance during the 1990s, with yields for the mid 2000s little different to the mid-1980s. However, in the last 5 years there has been a period of erratic but strengthening yield improvement since 2004, culminating in the highest ever national average oilseed rape yield in 2011 (3.9 t/ha).

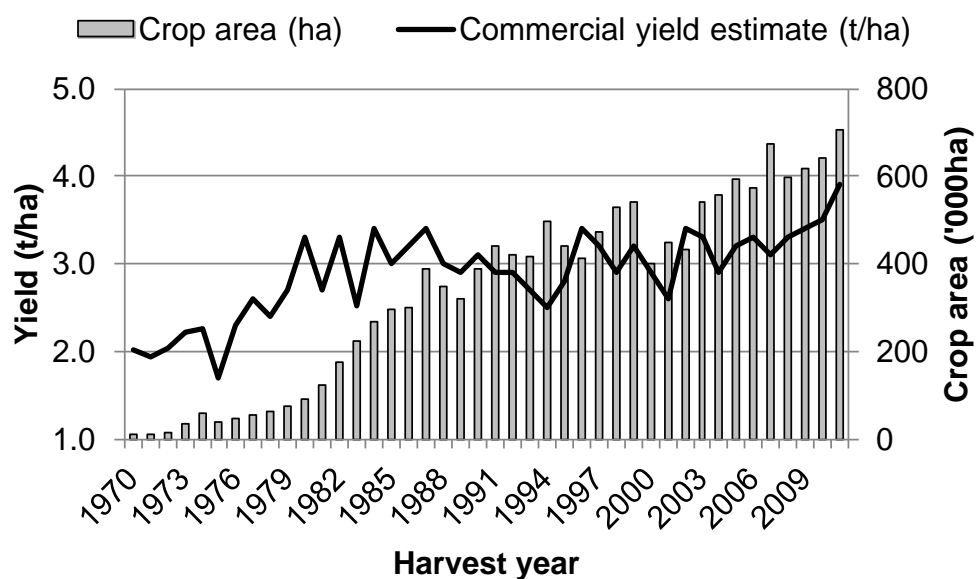


Figure 2. UK national average oilseed rape yield and production area from 1970 to 2011.

With its favourable environment for achieving high wheat and oilseed rape yields, and a skilled and efficient farming industry, the UK is well placed to respond to the challenges of rising global food demand, by ensuring a competitive and resilient production industry and secure domestic supply. Theoretical future yield potentials in the UK environment have been estimated at 19.2 t/ha for winter wheat (Sylvester-Bradley *et al.*, 2005) and 9.2 t/ha for oilseed rape (Berry & Spink, 2006). A less ambitious review (Defra 2005) estimated national average yields for 2025 and 2050 of 11.4 and 13.0 t/ha for wheat and 4.1 and 5.7 t/ha for oilseed rape. It has been estimated that applying management and genetic improvements from existing knowledge could raise national average wheat yields to 8.71 t/ha and oilseed rape yields to 3.88 t/ha (Spink *et al.*, 2009).

In the UK an integrated testing program is designed to identify and promote the use of improved varieties. To be commercialised, new varieties must undergo statutory National List (NL) trials over a two year period. The most promising varieties are selected for inclusion in HGCA Recommended List (RL) trials and at the end of their candidate year they may be added to the RL and promoted widely to growers. Varieties completing NL trials are required to demonstrate an improvement over the average of the current NL. For wheat this takes into account grain yield, specific weight, straw strength and disease resistance. In the case of oilseed rape it takes into account gross output (yield adjusted for the value of oil content in the seed) standing ability and disease resistance.

From analysis of variety trials, which have directly comparable seasonal fluctuations, it is known that the genetic gain delivered by plant breeders has proceeded at more than 0.5% per annum for wheat yield and about 2% for oilseed rape (Mackay *et al.*, 2010; Kightley & Horwell, 2011). Farm yield trends suggest that either plant breeding benefits are not being realised on farm, or are being negated by losses elsewhere in the production process. This could be the result of weather-related

seasonal influences, or agronomic limitations related to rotation, soil management, crop nutrition or crop protection, resulting from economic drivers, legislation or policy constraints.

Weather patterns and seasonal variability can be important determinants of crop performance. The last 100 years has seen a slow increase in UK temperatures, particularly in autumn and spring (Appendix Figures 1 & 2). Seasonal rainfall patterns are highly variable and show weakly positive trends for spring, autumn and winter (Appendix Figure 3), whereas summer rainfall shows a weakly negative trend. Trends for total sunshine hours (available from 1929) are weakly positive for spring, autumn and winter (Appendix Figure 4) but summer sunshine hours are very variable.

Since the Second World War agriculture has experienced a number of policies directed towards production as well as social and environmental goals. In the 1970's, the UK entered a Common Agricultural Policy that was productionist in nature and responded by increasing productivity and yields. Figure 3 shows output, input and total factor productivity (TFP) growth for all agriculture from 1973 to 2000 (Thirtle *et al.*, 2004). Output increased substantially, by an average of 1.7% per annum from 1973 to 1985, but then plateaued. Inputs also grew at a high rate but began to slow down from the mid-1980s. This leads to positive growth rates for productivity in this early period of 1.2% per annum, which then falls to an average of below 0.5% per annum from 1986 onwards.

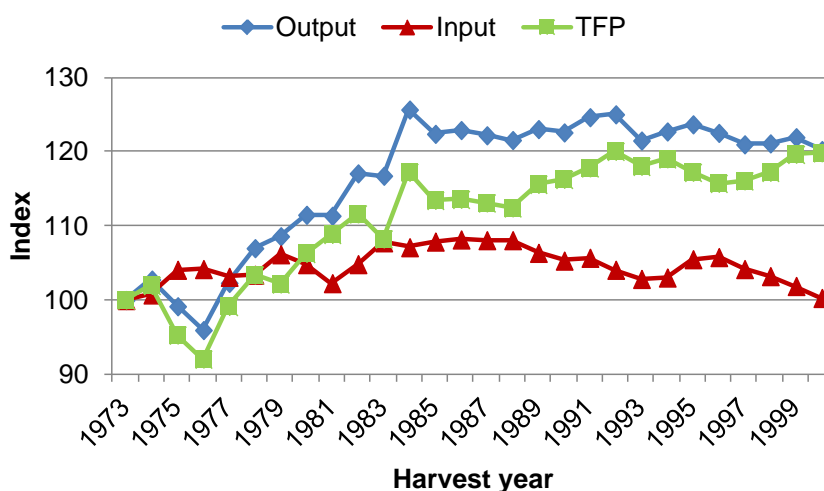


Figure 3. Index of Output, input and total factor productivity (TFP) for UK agriculture (1973=100).

Figures produced by Defra (www.defra.gov.uk/statistics/foodfarm/farmmanage/agriaccount/) on Total Income from Farming (TIFF), which is effectively the aggregate profit, provide a measure of performance of the whole UK agricultural industry. In real terms (at 2011 prices) TIFF rose from an average of £4.5bn in the 1980s to over £7bn in 1995 and 1996. It then fell sharply, staying below £4bn between 1998 and 2007. Only since then has TIFF returned to the levels seen in the early 1980s. The proportion of TIFF due to cereals or general cropping is not available. However, Defra figures (available at <http://www.defra.gov.uk/statistics/foodfarm/farmmanage/fbs/publications/>)

show that in real terms (at 2010/11 prices) Net Farm Income (NFI) for cereals grew from £4,600 per farm in 1987/88 to a peak of £73,100 in 1996/97, but then fell to a low of £7,700 in 2001/02. Average NFI for cereals has averaged £46,550 since 2006/07, though with a great degree of variability. General cropping follows a similar pattern, reaching a peak of £101,300 per farm in 1995/96. In the last recorded year of 2010/11, NFI for cereals and general cropping has reached £69,200 and £92,200 respectively, close to the peak values observed in the mid-1990s.

Closing the yield gap between average farm yields and what is achievable from the top varieties grown under average environmental conditions and managed with best practice management (as might be estimated from a crop model simulation or carefully managed trials) is an important goal for raising the productivity of UK agriculture.

3.1.2. Aims

The aims of this study were to identify agronomic factors that may be constraining wheat or oilseed rape yield improvement, assess the scope and opportunities for raising national yields through agronomy and highlight knowledge gaps or barriers to be addressed. Specific objectives included:

1. A review of existing evidence for agronomy as a contributory cause of yield plateau in wheat and oilseed rape, in the context of genetic improvement, changing weather patterns and other potential limitations, to define further the focus of the study.
2. The examination of farm yield trends alongside national data sets for crop price, fertiliser or pesticide usage and other agronomic factors.
3. The use of farm specific data to identify yield trends for shared character situations and to investigate differences in, or changes to, agronomic practice that may be related to yield trends.
4. The examination of existing research evidence to quantify the likely yield impact of differences in, or changes to, farm practice or crop management.
5. An assessment of the opportunities for, and barriers to, overcoming agronomic limitations to yield with respect to: their relative importance; approaches to overcoming them (research gaps or knowledge transfer required); barriers to overcoming them (economics, legislation, farm practice, farmer behaviour); potential environmental impacts and quality and end-use considerations.
6. Consult with Industry and utilise knowledge transfer opportunities to discuss and disseminate findings as appropriate.

A key deliverable was a list of recommendations for change, and research or knowledge transfer priorities, to achieve short-medium term improvements to crop management practice that could contribute to the re-establishing of rising average farm yield trends for wheat and oilseed rape.

3.2. Materials and methods

3.2.1. Objective 1: Review of evidence

A number of published papers and reports have investigated yield trends, notably for wheat, in countries around the World. These include studies that have used statistical modelling of yields over time to identify the time of occurrence of yield plateau, and analyses that have sought to determine the relative contribution of genetic, climatic, economic and agronomic factors to yield stagnation. Relevant reports for climatically similar regions of Europe were reviewed; notably recent studies from France (Brisson *et al.*, 2010) and Denmark (Petersen *et al.*, 2010). The findings of the review were used to help guide subsequent more detailed investigations of UK data.

National and regional yield trends for wheat and oilseed rape were defined using data abstracted from Defra statistics (<http://www.defra.gov.uk/statistics/foodfarm/food/cereals/cerealsoilseed/>). Comprehensive data relating to crop areas are collected in the June Survey for Agriculture and Horticulture. The full methodology is available at <http://www.defra.gov.uk/statistics/files/defra-stats-foodfarm-landuselivestock-june-junemethodology-20120126.pdf>. The Cereal Production Survey gathers data on production tonnages and moisture contents, and confirms planted areas gathered from the June Survey. This is done via a further survey of a stratified subset of respondents to the June Survey, with the methodology described at <http://www.defra.gov.uk/statistics/files/defra-stats-foodfarm-landuselivestock-june-statsrelease-uk-120530.pdf>. Cereal production figures include tail corn, cereals still to be harvested for grain, grain to be crimped and cereals intended for seed production. The figures exclude crops which have become unfit for harvesting, carry-over stocks from the 2010 harvest, bought in grain and crops harvested as whole-crop for silage.

These data are used to calculate yield estimates for each region in England and applied to June regional crop areas to derive production estimates for the whole country. In 2011, 3,500 survey forms were sent out with 2,768 responses for cereal production. Yield estimates for oilseed rape are derived using a similar approach but based on the Oilseed Rape Production Survey, a 'representative' sample of oilseed rape growers across English regions. In 2011 this comprised 624 responses. A similar methodology has been used for cereals in the other three countries, although yield data for Wales may rely on values from neighbouring English regions.

For wheat, detailed investigation of yield trends focused mainly on the 32-year period from 1980 to 2011, covering the 16 years prior to and following the apparent onset of yield plateau in the UK. For oilseed rape the period since 1984 was considered most relevant for analysis, as it represents the double-low era during which varieties low in glucosinolates and erucic acid have dominated production. Before this period the yield trendline is distorted by a progressive switchover from low yielding spring types to higher yielding winter varieties. Early winter varieties went through a phase

of very rapid turnover as a consequence of new quality criteria being imposed and this further contributed to yield variability. It was therefore concluded that attempting to analyse the pre 1984 yield trend in the context of environmental influences or agronomic practice was not appropriate.

Published analyses have used historical datasets comprising yields of winter wheat and winter oilseed rape from official UK NL and RL trials to examine the contribution of genetic improvement to yield trends recorded in trials. These analyses were reviewed to quantify the likely impact of genetics on observed trends in national average farm yields, and to enable the net impact of the growing environment (seasonal weather / climate or crop management) to be determined.

There is a large amount of year-to-year-variation in national yields that is likely to have resulted from weather variability, and that could obscure yield trends. The extreme nature of the 2000/01 season (a wet autumn that delayed sowing of many crops, followed by a dry spring) is a good example. A number of monthly and seasonal weather parameters were examined to determine the extent to which these may have influenced UK yields. Analyses focused on air temperatures, total rainfall and sunshine hours (long term solar radiation data were not available). Monthly mean data for temperatures, rainfall and sunshine were sourced separately for the UK and England from the Met Office website (<http://www.metoffice.gov.uk/weather/uk/climate.html>), and supplemented by daily temperature data from the Hadley Centre Central England Temperature (HadCET) dataset (<http://www.metoffice.gov.uk/hadobs/hadcet/data/download.html>) and the permanent weather station at NIAB Cambridge. Data for soil moisture deficit (SMD) were obtained from MORECS (<http://www.metoffice.gov.uk/services/industry/data/general>). This data is organised in 40km square 'cells', two of which were selected within areas that grow a significant area of wheat, one in the drier east and the other in the higher rainfall west of England. Cell 140 covers part of Cambridgeshire, while cell 178 covers part of Somerset. To investigate crop yield interactions, monthly data were used for rainfall, SMD (wheat only) sunshine hours and mean, minimum and maximum temperatures. For wheat two analyses were undertaken: the full 1911-2011 dataset and the period since 1980. For oilseed rape the analysis focused on 1984 onwards to coincide with the double-low variety era. Interactions for the two crops are discussed separately. Yield data were detrended by fitting a smoothing spline by linear regression to give predicted yields and used to further examine interactions with weather data.

3.2.2. Objective 2: Yield trends in context

There are a number of indicators that can be used to examine aspects of the translation of genetic improvement into national yield trends. However, there are also knowledge gaps and areas of partial knowledge, which limit the effectiveness of such exercises. Potential yield improvement on farm has been determined using seed certification data as a guide to the variety mix sown in each year, and from relative NL and RL trial yields of each variety included. For oilseed rape two factors

cannot be evaluated with any great degree of certainty: the influence of farm saved seed and that of imported seed which accounts for the majority of hybrid seed. Data on the actual uptake of oilseed varieties has been collected by recent HGCA and NIAB TAG planting surveys.

NL and RL variety trials are conducted under carefully managed and defined conditions that often differ from those within typical farm practice. Improvements in yield potential of new varieties that are evident within RL trials may not be fully expressed in farm situations, due to greater number of potential limitations in terms of site conditions and management practices across the country. Recent trends in RL variety yields from harvest 2002 to 2011 were investigated by presenting RL data by climatic region and several agronomic factors. These were compared with UK farm averages to pinpoint similarities or differences that could help to explain farm yield trends. For each year mean yields were calculated for control varieties (usually five) and for those in their first and second years on the RL (of which there were between three and seven in each harvest year).

For this exercise annual yield trends were estimated using varieties in their first year on the RL (year 1 varieties). Generally, varieties in their second year (year 2 varieties) had a similar trend to year 1 varieties, and provided a quality check on the yield trend. Although the composition of the year 1 and year 2 varieties changed each year, the same varieties were present for each factor within a year. This allowed for main effects such as climatic region, sowing date and soil types to be compared. Some new varieties will have included traits such as good disease resistance at the expense of yield. Furthermore, the means for year 1 and year 2 varieties comprise different nabim Groups, rather than the highest yielding varieties alone. However, over time, yields would be expected to increase as breeders' higher yielding selections were represented across the various nabim categories. Similarly, the year 1 and year 2 varieties would over time be representative of the new varieties grown on farm.

Crop selection and management practice are influenced by fluctuations in crop value and by economics. Fertiliser and pesticide usage are influenced by their cost, by government policies or legislation that regulate their deployment or availability and by voluntary initiatives that ensure appropriate practices to minimise pollution or other adverse impacts. Crop prices and key policy developments were charted alongside yield trends to identify possible associations between economic factors and declining yield improvements, and to highlight possible barriers to be overcome if recommendations for improvements to agronomy are to be adopted. In order to explore the relationships between various policy and economic factors a regression analysis was run on the causal factors against both OSR and wheat yield change over a long time series, using a so-called vector auto regression model. This model is based on regression techniques but includes a lagged dependant variable to explain variances in yield. Effectively, this explores the

impact of a previous year's yield on the present yield levels, as a means to capture decision making towards planting and investing in arable production. In equation terms the formula is:

$$Y_t = \alpha + \beta_1 Y_{t-1} + \beta_2 xp^1_{t-1} + \beta_3 xp^2_{t-1} + \beta_4 d93 + \beta_5 d05 + \beta_6 W_t + e$$

Where (Y_t) is yield in time t , (Y_{t-1}) is yield in the previous year, xp^1 and xp^2 are grain prices for feed wheat and breadmaking wheat respectively, lagged by one year to reflect the impact of past price change to present cropping decisions, two policy dummies ($d93$, $d05$) were included to reflect the MacSharry and Fischler reforms of the CAP respectively. W is a weather index, constructed as a ratio of annual average temperature to annual average rainfall over the analysis period. An index was then constructed using the value for 2000 as a base year. This aimed to capture some of the variances in yield due to weather. In addition a constant term (α) is included, and the explanatory variables (β) represent the yield impact of each variable. An error term (e) is included to capture factors which influence yield other than those specified above. Prices were deflated, using Defra price indices, to remove inflation effects from the series. All series were then standardised (by dividing by the mean) and converted into natural logarithms, in order to normalise the data.

National survey data were accessed to evaluate changes in fertiliser and agrochemical use, in the context of the fertiliser and crop protection requirements of new varieties and potential implications for wheat and oilseed rape yields. Surveys included the annual British Survey of Fertiliser Practice (<http://www.defra.gov.uk/statistics/foodfarm/enviro/fertiliserpractice/>) and biennial Pesticide Usage Survey (<http://www.fera.defra.gov.uk/scienceResearch/science/lus/pesticideUsageFullReports.cfm>), both of which cover the whole of Great Britain, plus the annual Farm Practices Survey for England (<http://www.defra.gov.uk/statistics/foodfarm/enviro/farmpractice/>). As a further potential indicator of crop management, trends in average wheat grain quality from the HGCA Cereal Quality Survey (<http://www.hgca.com/content.output/100/100/Markets/Markets/Survey%20Results.msp>) were also analysed. This is conducted annually by HGCA on behalf of the industry, with results based on about 69,000 samples of wheat obtained from laboratories around Great Britain. Each sample result provides information on variety and region of origin and for wheat contains data on one or more of moisture content, protein content, Hagberg Falling Number and specific weight.

Annual surveys of winter wheat disease in commercially treated farm crops across England have been conducted since 1975 (<http://www.cropmonitor.co.uk>). Approximately 300 wheat crops have been assessed annually during the grain milky ripe stage (GS73-75), with 25 tillers from each crop examined for stem, leaf and ear diseases. Background agronomic information is also collected. Annual surveys of winter oilseed rape disease in commercially treated farm crops have been undertaken since 1987. Approximately 100 crops have been monitored for diseases at three times throughout the season, with 25 plants from each crop assessed in the autumn during leaf

production, in spring and in summer during pod ripening. National pest monitoring has also been carried out in some seasons, with assessments on up to four occasions during the season. These have been based on 25 plants from each of 100 crops assessed in the autumn during leaf production and 50 crops in spring at stem extension, and up to two assessments carried out on twenty plants in situ in 40-60 crops at the early and late flowering growth stages in the summer.

In all cases, factors showing evidence of meaningful change (trends or annual variation) were charted over time and compared to changes in national average yields (trends or annual variation) over that time, with an estimate made of the potential qualitative or quantitative yield impact that could result from the level of variation observed.

3.2.3. Objective 3: Farm-specific data

Data from the Farm Business Survey in England (<http://www.farmbusinesssurvey.co.uk/>) were analysed by the University of Cambridge, Department of Land Economy. Yield data were available for about 800 farms per year for wheat and 400 farms per year for oilseed rape, between 1987 and 2009. It had been intended to group farms according to common factors such as predominant soil type, rainfall and disease pressure (shared character groupings). However, the numbers of farms available within each group were insufficient to permit this, other than to examine wheat yields by sub-region. Expenditure on key inputs, plus labour, contract and machinery costs, were available for approximately 200 farms per year for wheat and 90 per year for oilseed rape, but only over the six year period from 2004 to 2009. These were used to identify differences in approach to crop husbandry between farms in the top and bottom yield quartiles for wheat and oilseed rape, and relationships between cropped area, average yield and gross margins.

In order to enable yield trends to be examined alongside detailed agronomic data from the same farms, a number of case study farms were identified from contacts of NIAB TAG or SAC. Yields will have been influenced by a range of agronomic and weather factors each year, so the purpose of this exercise was to compare different approaches on farm, not to examine individual effects in isolation. Growers were asked about their strategies for winter wheat and oilseed rape production since the 1990s and changes to their farming systems, and quantitative and qualitative information was collected on soil type, crop area, variety choice, rotation, fertiliser inputs, cultivation practices and sowing dates, over a 16 year period between 1996 and 2011. Data prior to this were either not available or considered unreliable. Crop protection data were not collected, as this was considered to be of a good standard on the chosen farms, such that little of value was likely to have been learned relative to the large amount of extra information that would need to have been collected. Farms that had apparently ‘bucked the trend’ by managing to achieve increasing yield trends during recent years were given particular consideration.

3.2.4. Objective 4: Yield impacts from previous research

The analyses conducted within objectives 1-3 sought to identify some of the key factors that may have contributed to yield trends. However, there will have been many interactions between them. A review of research was undertaken to help quantify, using results of controlled field experiments, the potential contributions of the key individual agronomic factors to yield and yield stability from year to year and site to site. Data sources included published research reviews and reports from AHDB-HGCA (<http://www.hgca.com>). In addition, SAC and NIAB TAG have extensive data sets from published or unpublished agronomy experiments, investigating responses to fertiliser or pesticide inputs, cultivations and rotations, under commercially realistic conditions and in the main arable areas of the UK. These were used to quantify likely yield effects, and scaled up to provide an estimate of the potential impact the factor may have had on national average yield trends.

3.2.5. Objective 5: Overcoming yield limitations

Opportunities for overcoming key agronomic yield limitations were assessed, as well as potential barriers. Recommendations have been made relating to knowledge transfer (where understanding is considered to exist but has not been adopted widely enough in commercial practice) or further research (where gaps in understanding need to be addressed before changes to agronomic practice can be advocated). Potential constraints to adoption of the recommended changes to agronomy were evaluated, including economics and practical feasibility. Legislative requirements, policy constraints, and farmer behaviour were also considered. The potential environmental impacts of the recommendations were estimated, and grain quality and end use considerations (in particular protein content in wheat and oil content in oilseed rape) identified based on existing experimental data and a physiological understanding of crop growth, yield and quality formation.

3.2.6. Objective 6: Industry consultation and knowledge exchange

Consultation with industry representatives was a key component of the knowledge exchange and reporting process. This included a dedicated stakeholder meeting with farmer, agronomist, plant breeder and researcher representatives. This provided an opportunity to capture knowledge and experience, largely from a more practical rather than a scientific perspective, and to help focus the study and interpret the data. Further discussions with industry helped to refine the preliminary conclusions and recommendations. Notes from the stakeholder meeting and from email exchanges that stemmed from this are recorded in appendix 5.

3.3. Limitations

3.3.1. Scope of the study

This initial study has examined the possible contribution of a wide range of agronomic factors to recent national yield trends, in the context of other potentially important influences. It has focused on farm yields and practices, rather than research trials. Yield potential using substantially-modified agronomic practices and technology-related yield gaps that might exist have not been considered. This could be a useful objective for further work. The report is not therefore intended to provide a complete and fundamental evaluation of the scope for yield enhancement in the UK.

3.3.2. Data sources and reliability

The study was heavily dependent on published and unpublished surveys, the accuracy of which is limited by the scale and sophistication of their sampling methodologies. Defra data relating to crop production are obtained from the June Survey for Agriculture and Horticulture. A full census is required every 10 years but a partial sampling is undertaken in the intervening years. In the last decade the sampling rate varied from 40.7% (2002) to 18.5% of holdings (2009), but during the 1990s sampling was regularly over 70%. In 2011 30,000 surveys were sent out (28.6% of holdings) with a 73% response rate.

Yield data is derived from production data and cropped areas obtained through a follow-up survey of a subset of June survey respondents. In 2011 these were based on 2,768 responses for cereals and only 624 responses for oilseed rape, which are then scaled up using regional cropped areas from the June Survey. Although the percentage of holdings surveyed each year is still reasonable, with the decline in proportion of holdings surveyed for cropped area, and the small proportion of holdings subsequently surveyed to derive yield estimates, there must be some uncertainty as to potential change in the accuracy of national yield estimates over the time periods studied.

Surveys have also been limited by the level of detail requested. There has been no differentiation between winter and spring wheat cropping in the June Survey, and winter and spring oilseed rape cropping have been recorded separately only since 1999.

Comprehensive national weather data were available for the period studied, but there has been no systematic collection of photosynthetically active radiation (PAR) data over the UK. It is recognised that, as a surrogate for solar radiation, sunshine hours have limitations, including changes to the measurement method. However, for the scope of this study they proved to be a useful indicator. Soil moisture deficit (SMD) data were not freely available, such that examination of this was limited to specific locations. A more extensive analysis of SMD trends would be useful in further studies.

Hard evidence on the commercial uptake of varieties was very scarce, and a better knowledge of this is considered important to the understanding of yield trends and fluctuations. Reasonable estimates were possible for wheat, where most certified seed is produced in the UK, although farm saved seed is not documented. This was more difficult for oilseed rape as multiplication rates are much higher and there is thought to be more speculative seed production. Farm saved seed again complicates the picture and oilseed rape seed is also more likely to be imported than wheat.

3.3.3. Analyses

While wheat is known to have been dominated by winter cropping, proportions of winter and spring rape have been more variable. The impact of the lower yielding spring rape crop on the combined winter and spring national yield trend has been estimated in this report, but it was too speculative to try to relate changes in agronomic practice to just the estimated winter oilseed rape yield trend.

For this study, testing of weather effects was limited to single and multiple correlations of yield with weather variables, and an examination of trends over time in key factors. It is acknowledged that this does not provide a proper assessment of the potential impact of climate trends on national yields, which could for example be explored through the use of a suitable crop model. However, this was considered to be outside of the scope of this study.

3.3.4. Unknowns

There were a number of potentially important agronomic factors for which little or no data were available, in particular trends over time. These are highlighted throughout the report, and where appropriate recommendations have been made to as to additional data that should be collected in future. Together, they could account for a significant proportion of the unexplained yield effects over part or all of the time periods studied.

3.4. Results: Wheat

3.4.1. Literature review

Global Wheat Yield Trends

Wheat yield trends have unsurprisingly already been the subject of a number of previous studies. Calderini & Slafer (1998) analysed trends in 21 countries (including Argentina, Australia, Canada, New Zealand, USA and several European countries) from the start of the 20th Century. Even at this early stage, it was identified that yield gains in many countries had apparently been levelling off during the 1990s. Lin & Huybers (2012) developed a statistical test for whether or not a yield time series had levelled off and applied it to wheat yields around the world. Of the 50 regions tested for yield stagnation, 27 showed yields that had levelled off when tested at the 80% confidence level,

including much of Western Europe, Colombia, Bangladesh, India, Romania, Western USA and Zambia, between them accounting for some 35% of global wheat production. 18 regions were found to have levelled off at the 95% confidence level.

A rising-plateau regression analysis by Brisson *et al.* (2010) indicated that the period over which yield stagnation had begun in France ranged from 1991 to 1998 depending on region, with 1996 the most frequent year. Similar results were reported for other European countries, including Denmark (1995), Netherlands (1993), Switzerland (1990) and UK (1996). Neither Lin & Huybers (2012) nor Brisson *et al.* (2010) were able to show significant deviations from a linear yield increase for Italy or Spain, and the year of stagnation for Germany was later than for other Western European Countries. According to Petersen *et al.* (2010) the average annual yield increase for winter wheat in Denmark was 0.08 t/ha between 1961 and 2007, but from the end of the 1990s the increase had been uneven and close to zero. Finger (2010) described the levelling off of wheat and other cereal yields in Switzerland since the early 1990s, and Peltonen-Sainio *et al.* (2009) noted the levelling off of wheat yields in Finland since 1995 (and a decline in the yields of other cereals).

Determining the causes of yield stagnation with any certainty has proved to be a more complex problem. Petersen *et al.* (2010) noted that the number of available datasets was limited, and the ability to analyse and interpret individual factors was often restricted by yields being affected by several simultaneous and inseparable factors. Crop yields depend partly on the genetic potential of the varieties being grown, so this has been the starting point for many of the previous studies.

Genetics and yield potential

Evans & Fischer (1999) observed that progress through conventional breeding in yield potential (defined as the yield of a variety when grown in environments to which it is adapted, with nutrients and water non-limiting and with pests, diseases, weeds, lodging and other stresses effectively controlled) was apparent in many crops, and that this had been significant for yield progress at farm level under a wide range of conditions.

There is little evidence of variety improvement in UK yield records leading up to the Second World War, and it is generally accepted that much of the early post-war yield increase came from improved management practice. The big breakthrough came with the introduction of semi-dwarf varieties (Bingham, 1972) that now represent 70% of the world wheat acreage. The change in the balance of competition for photosynthates between stem and ear gave an immediate improvement in yield. Combined with better lodging resistance that accompanied the semi-dwarfing characters, the improved quality (and Chorleywood baking process) and good disease resistance that became available, performance of new variety types led to a tremendous expansion of the crop to 2M hectares and national average yields hitting 8 t/ha by the late 1980s.

According to Spink *et al.* (2009), yields of new wheat varieties have increased by about 0.7 t/ha per decade in recent years, but they concluded that genetic gains have diminished since 2002. This was blamed on the end of government-sponsored breeding programmes, poor profitability (leading to insufficient investment), exhaustion of past innovations, constraints on new breeding technologies and the wide spectrum of other trait priorities for breeders. Shearman *et al.* (2005) concluded that genetic gains over the period 1972-1995 were positively correlated with harvest index and above-ground biomass, and based on a combination of improved growth rate and radiation use efficiency in the pre-anthesis period, leading to increases in number of grains per square metre, and a larger source for grain filling through increases in soluble carbohydrate reserves in the stem at flowering.

Also using data from RL trials, Fischer & Edmeades (2010) estimated the contribution from plant breeding to UK winter wheat yields over the last two decades as 0.061 t/ha, concluding that this was comparable with the rate of improvement in farm yields since 1989 (0.053 t/ha), assuming a linear increase over that time. Using a similar approach Peltonen-Sainio *et al.* (2009) estimated annual genetic yield progress as 0.05 t/ha for winter wheat in Finland.

Recent studies of UK trials data indicate that genetic gain in wheat varieties is linear. Mackay *et al.* (2010) analysed yield trends for varieties in Recommended List (RL) and National List (NL) trials, to illustrate yield improvement for a number of crops between 1948 and 2007. Rate of change was analysed for the whole period and for two subsets of years: 1948-1981 and 1982-2007. There was an overall linear improvement, attributable to varieties, of 0.071 t/ha per annum. Between 1948 and 1981 the contribution of plant breeding to yield improvement in winter wheat had been estimated at 60% (0.061 t/ha per year), with 40% (0.041 t/ha per year) due to growing environment (climate or husbandry factors). But since 1982 it was estimated that plant breeding had contributed at least 88% (0.074 t/ha per year) of the yield improvement, with little evidence of a contribution from the growing environment. In contrast, for sugar beet and maize since 1982 it was concluded that plant breeding and environmental contributions had been similar (around 50% each).

In a series of field experiments between 2008 and 2010 that evaluated 64 UK, French and other elite varieties (the 'ERYCC panel') released between 1953 and 2008, Clarke *et al.* (2012) found that breeders have increased yield potential by about 0.5 t/ha per decade (equivalent to 0.05 t/ha per year) over the 50 or so years represented. Yield increases were associated with improvements in the number of grains per ear and soluble stem reserves. An increase in the number of grains per m² found was associated with increased ears per m² and a faster crop growth rate pre-flowering.

Kightley (2011) compared trends in yield potential in wheat and oilseed rape for the period from 1984-2010, as shown by those varieties expressing a yield improvement above the previous best, using NIAB Classified List data, a composite of RL and NL data. Overall, yield improvement had progressed at 0.57% per year for wheat, starting with Riband (first tested in 1985) and culminating with KW Santiago (first tested in 2008). This compared with an estimated 2% per year increase for oilseed rape for the same period. Plant breeding delivers a constant flow of new varieties but yield is only one objective and has to be balanced against disease resistance, end-use quality and field characters if varieties are to succeed commercially. Part of the breeding effort for wheat is focused on higher value bread-making varieties, which are generally lower yielding than feed wheats. Since 2004, the number of varieties delivering an absolute yield advance is surprisingly small, with incremental yield progression represented by just 6 wheat varieties. For oilseed rape, essentially targeting a single commodity market, 18 varieties were associated with the improving yield trend.

Analysis of official variety trials by Brisson *et al.* (2010) indicated that genetic progress in France had resulted in an increase in yield potential of about 0.1 t/ha per year (based on the 20 best varieties), largely due to increased harvest index. A slightly larger increase in untreated wheat yields (0.13 t/ha per year) was calculated, suggesting a supplementary improvement in disease resistance. It was noted that in some regions growers had been increasingly opting for high protein breadmaking wheats and not necessarily selecting the highest yielding varieties, leading to a potential over-estimate of the genetic contribution at farm level.

Petersen *et al.* (2010) considered that breeding was one of the few factors to have had a positive impact on the yield of winter wheat in Denmark. Comparing yields of new against older reference varieties, the increase in potential yield due to breeding progress was estimated at 0.09 t/ha per year between 1980 and 2007. However, it was noted that yields of reference varieties may decline over time due to their diminishing resistance to disease or reduced adaptability to changes in the environment, which could overestimate the contribution of plant breeding.

Climate and weather

According to a recent Met Office report (Met Office, 2011), there has been warming over the UK since 1960 with greater warming in summer than winter. There has been a decreasing trend in the frequency of cool nights and cool days and an increasing trend in the frequency of warm nights and warm days. The occurrence of warm summer temperatures has become more frequent and cold summer temperatures less frequent.

Porter & Semenov (2005) pointed to the lower rates of increase in wheat yields in southern Europe (where temperature and rainfall conditions tend to be more extreme) compared to northern Europe, and an increase in the year-to-year variation in wheat yields, as evidence that climate warming

since the start of the 1990s has started to affect European wheat yields. Using the Broom's Barn Crop Growth Model and weather for eastern England, Jaggard *et al.* (2007) found that, between 1976 and 2004, two-thirds of the increase in sugar yields recorded in official sugar beet variety trials could be attributed to changing climate (partly through a trend towards earlier sowing). The evidence in their paper was that wheat yields had not benefitted from the same effects.

Average annual temperatures for the period 1991-2004 were 0.7-0.8°C higher than the 1961-1990 baseline in the major wheat and oilseed rape growing areas of England, and 0.5-0.6°C higher for Scotland and Northern Ireland (Perry, 2006). It is only since 1987 that the temperature trends have become more obvious. Increases have been largest in the winter and spring, and smallest in the autumn. Minimum temperatures have increased more than maximum in the summer, with the opposite true in the winter. Days of air frost in winter have decreased by 25-35%, with the main change occurring during the 1990s. All areas, but notably Scotland, experienced an increase in winter precipitation between 1961 and 2004, and from 1929 to 2004 autumn and winter sunshine increased by about 10 and 20% respectively for northern, central and south-east England.

Higher temperatures have only a limited effect on the interval between crop emergence and the start of stem extension for winter wheat and oilseed rape because they must undergo vernalisation and experience an appropriate daylength before the switch to reproductive development can occur. The length of time between stem extension and flowering is more temperature dependent, and the duration of grain fill is limited by thermal time. In contrast, with little or no vernalisation requirement, the development of spring sown crops is accelerated by higher temperatures at all stages.

Monteith (1981) concluded that the two main climatic causes of variation in the yield of winter and spring sown crops growing in eastern England were temperature and rainfall and that their effects were much greater than those caused by variation in incident radiation. It was calculated that 12% of the yield variation of winter cereals resulted from variation in temperature, radiation and rainfall on heavy land, rising to 17% on lighter soils.

The light-saturated photosynthetic rate of wheat reaches its maximum at temperatures from about 20–32°C, whereas total crop respiration shows a steep nonlinear increase for temperatures from 15–40°C (Porter & Semenov, 2005). This would suggest that net losses due to respiration may be increasing in the UK as a result of the rising minimum (or night-time) temperatures. Monteith (1981) showed that warmer temperatures during grain fill reduce yield. When wheat plants were transferred to high temperature rooms 7 days after the first anthers appeared, grain weight of an Australian wheat variety at maturity was reduced by about 5% for each 1 °C rise in daily mean temperature in the range from 17.7 to 32.7°C (Tashiro & Wardlaw, 1989). This was largely due to a

reduction in the duration of grain growth, but with a reduction in grain growth rate above a daily mean temperature of 26.7°C (or a maximum of 30°C and minimum of 25°C).

Wheat grain number can be reduced if a variety that is sensitive to heat stress is exposed to a period of high temperature around anthesis. Mitchell *et al.* (1993) observed that a temperature of 27°C or higher applied mid-way through anthesis could result in a reduction in grain number, but with less impact on yield due to compensatory increases in grain size. Wheeler *et al.* (1996) showed that grain numbers were reduced by a temperature of 31°C or more immediately before anthesis. However, the frequency of occurrence of such high temperatures around the time of anthesis (in June) over the last two decades in the UK is likely to have been low, compared for example to more southerly areas of France.

Gooding *et al.* (2003) showed that drought and increased temperature before the end of grain fill shorten the grain filling period and reduce grain yield and mean grain weight. Grain filling is most severely affected by drought during the 14 days after anthesis. Overall yield losses due to drought for the UK wheat crop have previously been estimated at around 10-20% (Foulkes *et al.*, 2001). According to Spink *et al.* (2009) about 12% of the UK wheat crop is grown on drought prone land and is likely to experience yield limiting droughts in 2 out of 3 years. However, recent seasons would suggest that the area at risk could now be greater.

Global climate – crop yield relationships, and the impacts of warming, were examined by Lobell & Field (2007). They reported the likelihood of negative impacts on yield progress for wheat, maize and barley between 1981 and 2002, unless countered by adaptation measures (e.g. variety choice or earlier sowing). Significant yield effects were mainly attributable to warming temperature trends, with precipitation trends having only minor effects on yields. It was noted that the impact of global warming was likely to have been offset to some extent by increased CO₂ fertilisation, although to an uncertain extent.

Using historic weather records and a dynamic crop growth model, Kalra *et al.* (2008) identified increasing temperatures due to climate change as a cause of wheat yield stagnation in north-west India, with a 0.2–0.5 t/ha yield reduction per 1°C increase in temperature. Sowing date was identified as an appropriate adaptation strategy (with an increase in temperature of 1-3°C likely to advance optimum sowing date by 5-8 days per 1°C temperature rise). Warming climate conditions have also been implicated in decreasing yield trends in Bangladesh (Lobell *et al.*, 2011)

Brisson *et al.* (2010) concluded that changes to climate since 1990 have contributed to wheat yield stagnation in France, by negating some of the genetic gain. Estimated yield penalties calculated with two different models ranged between 0.021 and 0.046 t/ha per year, with a greater impact on

higher yielding crops grown in intensive cereal areas in the north. This would explain up to two-thirds of the limitation to yield gain observed in France (Arvalis, 2012). Main causes were identified as increased occurrence of drought during stem elongation, and high temperatures during grain fill.

Peterson *et al.* (2010) identified key weather changes in Denmark as increased summer and winter temperatures (averages for 2000-08 were 1.1 to 1.5 °C higher than the average for 1961-90), a slight tendency for increased winter precipitation and an increase in winter sunshine hours. Using multiple regression analysis over the period 1990-2008, the effects of winter temperatures and precipitation, spring sunshine hours and maximum summer temperature were found to affect national grain yields. A climate-normalised annual yield increase of 0.030 t/ha was estimated, compared to a 0.018 t/ha increase without correction for climate variability, indicating that climate changes have caused yield decreases over this period of 0.012 t/ha per year. However, it was noted that the accumulated increase in atmospheric CO₂ concentration between 1990 and 2008 (30 ppmv) would correspond to an estimated annual yield increase of 0.016 t/ha.

Hughes *et al.* (2011) showed that deterioration in average climate conditions has contributed significantly to the decline in estimated farm productivity over the post-2000 period in Australia. Differing responses were observed across regions and farm types, with the southern region showing greater climate sensitivity than northern and western regions. Cropping specialist farms were observed to be more sensitive to climate variability than mixed cropping–livestock farms.

Legislation and policy

Spink *et al.* (2009) identified restrictions to available chemistry, loss of actives and limitations to use, agricultural policies discouraging production, decoupling (of support payments from production) and the need for growers to invest in environment schemes as having contributed to the decline in wheat yield improvement in the UK. Peltonen-Sainio *et al.* (2009) categorised the last five decades in Finland into three agronomic phases: (1) between 1960 and 1980 agriculture was mechanised and improved basic agricultural practices were introduced, (2) between 1981 and 1994 more intensive crop management practices were increasingly applied and (3) between 1995 and 2005 EU changes resulted in alterations to agricultural policies and markets. It was concluded that a main reason for yield stagnation during this third phase had been the application of an environmental programme aimed at increasing agricultural sustainability. Finger (2010) also showed a relationship between the introduction of policy measures aimed at environmentally friendly cereal production, leading to widespread adoption of extensive farming practices, and an observed levelling-off of crop yields. Lin & Huybers (2012) noted that, with a few exceptions, plateauing yields have tended to occur in areas with adequate food security, whereas countries with historically greater food insecurity have generally shown continuing yield increases.

Economics and management intensity

The impact of the cost / price squeeze, leading to a decline in UK wheat gross margins especially between 1995 and 1997, was highlighted by Spink *et al.* (2009). It was observed that associated reductions in 'fixed' costs through economies of scale, fewer staff and reduced investment in plant and machinery resulted in declining management intensity per unit area, less accurate matching of inputs to requirement, reduced cultivations and poorer timeliness. Decreased economic incentives to produce intensively, as cereal prices fell and input prices remained unchanged, were identified as a further reason for yield stagnation in Finland (Peltonen-Sainio *et al.*, 2009).

Petersen *et al.* (2010) concluded that the estimated gap of up to 0.7 t/ha between potential net yield gains and actual yield increases achieved between 1990 and 2006 could partly be explained by low cereal grain prices leading to reduced management intensity. It was considered that, in order to optimise farm profitability, the likely reduction in working hours and reduced expenditure would have resulted in suboptimal timing of operations and reduced input rates. Evidence that yields of winter wheat varied considerably between farms indicated that much of the variation may be related to management. There had also been a shift towards larger farm and field sizes, with agronomy potentially less targeted to soil and field variability. However, it was noted that increased knowledge transfer and improved decision support systems may partly have compensated.

Higher productivity among large farms is usually assumed to be the result of increasing returns to scale. However, Sheng *et al.* (2011) found that constant or slightly decreasing returns to scale is more typical in Australia. Instead, it was found that large farms achieve higher productivity through changes in production technology, such that the ability of smaller farms to improve would depend more on their ability to access advanced technologies than their ability to expand. It was observed that some technologies may not be well suited to smaller farms e.g. better machinery might only be viable on farms above a certain size. In addition, small farms might not be able to easily reallocate resources due to limited business management ability, market access or availability of finance.

Comparison of farm yields with trials

Spink *et al.* (2009) reported a divergence between farm yields and those being achieved in RL trials, and attributed this partly to a widening gap in management and resource deployment and partly due to poorer soils on some farms. Key differences were listed as the number of fungicides applied, the use of ploughing rather than non-inversion tillage and sulphur fertiliser use. Jaggard *et al.* (2010) compared the yield gap between national average farm yields and those from official variety trials in the UK from the mid-1970s for sugar beet and the late 1980s for wheat until the late 2000s. For wheat it was observed that the yield gap had remained stable at about 2.3 t/ha, but for sugar where yields were rising more rapidly the gap between farm yields and trials had increased. It was noted that for sugar beet the top performing farms were achieving yields close to those seen

in trials, but yields for the poorer performing farms were less than half those seen in trials. This was not related differences in soil type or region, but loosely reflected the crop's access to water.

An analysis of treated plot data from more than 6000 wheat field experiments in Denmark between 1992 and 2008 revealed climate-corrected annual yield increases of 0.071 and 0.047 t/ha for sandy and loamy soils respectively (Kristensen *et al.*, 2011). This compared with climate-corrected national farm yield increases of 0.030 t/ha per year over a similar period, indicating that the causes of stagnating yields had been less manifest in controlled field experiments (Petersen *et al.* 2010). It was noted that the number of sites for variety field testing had been reduced over time and that since the mid-1990s these had typically been carried out at only a few well-managed sites on loamy soils, which could lead to bias when estimating the contribution from breeding progress.

Brisson *et al.* (2010) found parallel trends for three regions in France when comparisons were made between farm yields and trial yields at experimental stations where management practices were optimal and soils good. This led to the conclusion that the main causes of yield increase or decrease were the same regardless of whether or not growing conditions were optimal, and that it did not indicate a decline in farm agronomic practice that might negate genetic gain.

Agronomy

Nitrogen fertiliser use increased between 1996 and 2000 in France, but fell by about 20 kg N/ha (10-15%) between 2000 and 2007 (Brisson *et al.*, 2010). A change in the average number of applications from 2 to 3 was considered likely to have improved its efficiency of use, although this would not be expected to give a consistent improvement in efficiency of use in the UK. The likely net effect was estimated to be an average yield penalty of only 0.1 t/ha (range 0 - 0.2 t/ha, depending on soil type), equivalent to a 0.015 t/ha yield reduction per year between 2001 and 2007. As genetic progress had been associated with increased harvest index, it was assumed that crop N requirement had not increased.

In Denmark, the reduction in N fertiliser use and the way that the restrictions had been imposed were considered to have reduced yields (Peterson *et al.*, 2010). Based on a dataset of recorded N doses on farms from 1985-2007 and a set of 115 experimental yield-to-N rate responses carried out in well managed crops from 1998-2007, it was estimated that a yield reduction of 0.21-0.31 t/ha had been caused by the introduction of standard N rates and their subsequent reduction, in practice corresponding to 16-19 kg N/ha.

Overall yield losses from foliar disease in treated UK wheat crops were estimated at 3.6% for the 1990s, when yields started to plateau, compared to 5.3% for the 1970s (Hardwick *et al.*, 2000). The reduction in yield losses was explained by an increase in fungicide use. In France, no

significant changes in fungicide treatment frequency were observed in three major cereal-growing regions between 1995 and 2007, other than slight dips in 2002-04 corresponding to a fall in wheat prices, the use of strobilurin chemistry, and a drought season in 2003 (Brisson *et al.*, 2010). There was also no obvious relationship between low yields and high disease levels. In Denmark the reduction in fungicide use over the last two decades (in order to maximise margin rather than yield) is considered to have largely negated the benefits of more effective fungicides being introduced (Petersen *et al.*, 2010). No consistent increases in disease levels were identified.

In Denmark the frequency of attacks by grain aphids (*Sitobion avenae*) was observed to have fallen from 1992-2008 (Petersen *et al.*, 2010). Barley yellow dwarf virus (BYDV) and field slugs were not in general regarded as serious problems that could have contributed to stagnating yields. However, average yield penalties through failure to control orange wheat blossom midge (*Sitodiplosis mosellana*) were estimated at 0.04 t/ha. It was noted by Ellis (2009) that changes in climate and crop management could have affected the ability of crops to tolerate pests. It was concluded that the warming climate will have made autumn sown crops more tolerant of damage between plant emergence and the start of stem extension (e.g. to loss of plants or shoots), but this advantage may have been countered to some extent where seed rates have been reduced.

Petersen *et al.* (2010) found no evidence of changes in weed pressure, herbicide use or PGR use having affected yields. No other references were found linking weed control to yield trends.

Bingham (2011) pointed to deterioration of soil structure as a major factor in the stagnation of wheat yields and proposed that incorporation of straw, directly or as farmyard manure, should form part of the solution. Timeliness of field operations with heavy equipment was also implicated.

The potential for reduced yields where ploughing has been replaced by non-inversion or reduced tillage systems has been identified by several authors (Spink *et al.*, 2009; Petersen *et al.*, 2010).

In Denmark the yield of winter wheat under minimum tillage was found to be about the same as for ploughed soil, provided that grass weeds were controlled by herbicides and that the soil was loosened to 5-15 cm depth before sowing (Petersen *et al.*, 2010). Where grass weeds are present and where there are infestations of take-all in multiple wheat crops, then yield losses of 0.8-1.2 t/ha can occur. The area of minimum tillage in Denmark equated to only 10% of arable land, and it was estimated to have been used on only about 5% of land cropped with winter wheat, translating into a yield reduction of about 0.02 t/ha over the period since 1990. They concluded that the net effect of tillage on the yield of winter wheat in Denmark during the previous 3-4 decades was minor

A soil management factor of particular importance identified by Petersen *et al.* (2010) was yield reduction due to subsoil compaction. The permanent yield reduction from compaction of deep subsoil layers was estimated to be 2.5% across a range of soil types in humid climates. This was increased by slurry application; with application methods and axle weights being implicated in this effect. It was estimated that for the period 1990 to 2006, subsoil compaction would reduce yields by 0.1 t/ha. Brisson *et al.* (2010) found no evidence to implicate changes in soil organic matter being a cause of wheat yield plateau in France.

In France there has been a significant change since about 1999 in crops preceding wheat, with an increase in oilseed rape from 20 to 30%, at the expense of peas until 2003 and then maize (Brisson *et al.*, 2010). The inclusion of field beans has to some extent compensated for the reduction in peas since 2001. As wheat after oilseed rape yields less than after peas in France (by about 0.8 t/ha), it was estimated that this would equate to a reduction in yield of 0.42 t/ha for the period 1995-2006, equivalent to 0.035 t/ha per year.

In Denmark, there has been a trend towards a higher proportion of winter wheat in crop rotations (especially on the better soils) increasing the frequency of wheat following wheat from 20-30% of fields in the early 1990s to 40-50% since 2000 (Petersen *et al.*, 2010). This has led to an increased risk of yield losses due to soil-borne diseases such as take-all. The yield penalty for wheat after wheat compared to following other crops was estimated at 0.4 t/ha, but up to 1.0 t/ha compared to following a non-cereal break crop. 60% of the Danish wheat area was assumed to now be at risk from take-all, equivalent to a 0.24 t/ha yield reduction since 1990.

Barriers and Opportunities

Spink *et al.* (2009) estimated that half of the 'lost' yield of wheat could be recovered over 5 years by improved attention to management of inputs (equivalent to a 10% increase), but added that it could take 10 years to achieve management intensity improvements back to the level of the early 1980s, including addressing a shortfall in trained agronomists. Jaggard *et al.* (2010) observed that a large part of the yield increases needed must come from improved application of technologies that become available in future. It was suggested that this would require new agronomic studies to translate them to profitable tools or techniques for farmers, and trained extension personnel to deliver messages appropriately such that yields increase without adverse environmental effects.

Arvalis (2012) noted in France that as climate change accounted for a large part of the yield stagnation observed, overcoming the limitations could be achieved by adapting agronomy to climate, increasing the diversity of varieties on farm to select locally for those coping best with climate and more resilient to temperature, plus improved tools for decision support, access to innovations and KT.

Petersen *et al.* (2010) concluded that in Denmark grain and input prices are probably the main factors that have indirectly affected farm and crop management, but commented that relatively little is known about how price expectations affect crop management and the resulting yield effects, calling for further study. They also noted that some of the believed causes of yield loss were likely to persist, in reductions in N fertiliser doses and the higher frequency of wheat after wheat in rotations. Hence these were one-off effects, meaning that the annual yield increases as a result of breeding should translate more readily to national grain yields in the future, assuming improvement in crop management at the farm level is maintained.

Ransom *et al.* (2007) noted that identifying and exploiting positive genotype by (crop or farm) management interactions offers a potential avenue for increasing yield. It was suggested that imposing sustainable yield-improving management practices on breeding material during the selection process has scope for identifying genotypes with higher yield potential at the farm level when these management practices are employed.

3.4.2. Yield trends

National yield trend 1980 – 2011

This study is concentrating on the period between 1980 and 2011, which covers similar length spells of irregular yield improvement up to 1996, and then a plateau phase from 1996 to 2011. While it is possible to fit a second degree polynomial trendline to the yield data (Figure 4), a broken stick model accentuates the two phases (Figure 5). Though exhibiting considerable year to year variation, yields increased by an average of 0.105 t/ha per year between 1980 and 1996. But since then yields have shown little improvement, with an average increase of only 0.016 t/ha per year.

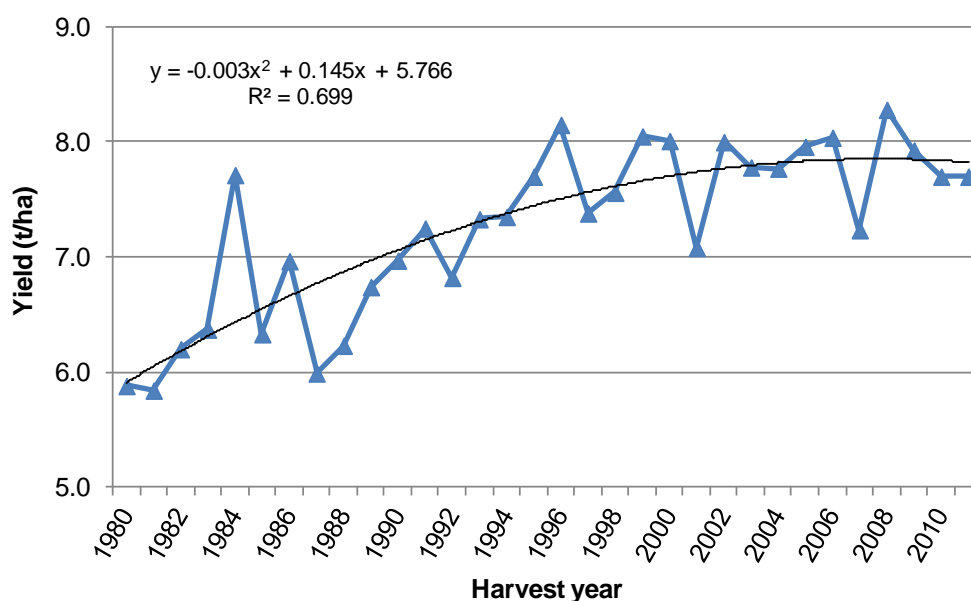


Figure 4. UK national average wheat yield trend from 1980 to 2011 ($x = 1$ for 1980).

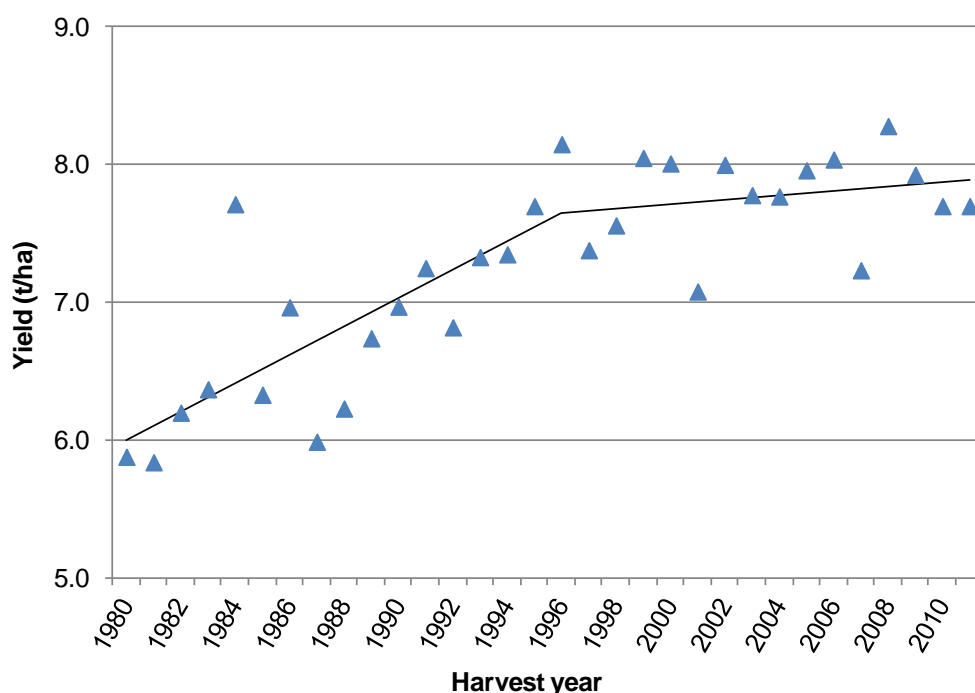


Figure 5. UK national average wheat yields from 1980 to 2011 (SE 1980-96 0.0233, 97-2011 0.0202).

Regional yield trends

Separate yield data are available since 1999 for the four home countries and eight English regions. Representing 93% of the UK wheat area, it is not surprising that the trend for England (Figure 7) is similar to that for the UK (Figure 6), with annual variation between 7.1 and 8.3 t/ha but little overall increase, plus dips in 2001 and 2007. Scotland and Wales show slightly different trends (Figure 7), influenced by relatively high yielding periods in the mid-2000s. Scottish yields have been higher than the UK average, only dropping below 8 t/ha on three occasions, while yields in Wales have been below the UK average, in the region of 7 t/ha. The small Northern Ireland crop has shown steady improvement, with yields increasing from just below 7 t/ha to just over 8 t/ha (Figure 7).

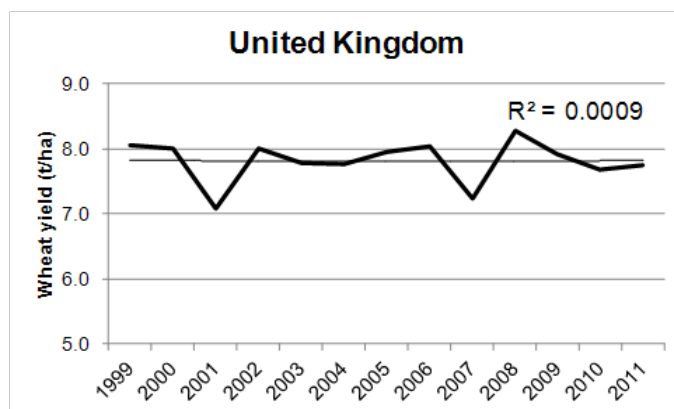


Figure 6. UK average wheat yield trend from 1999 to 2011

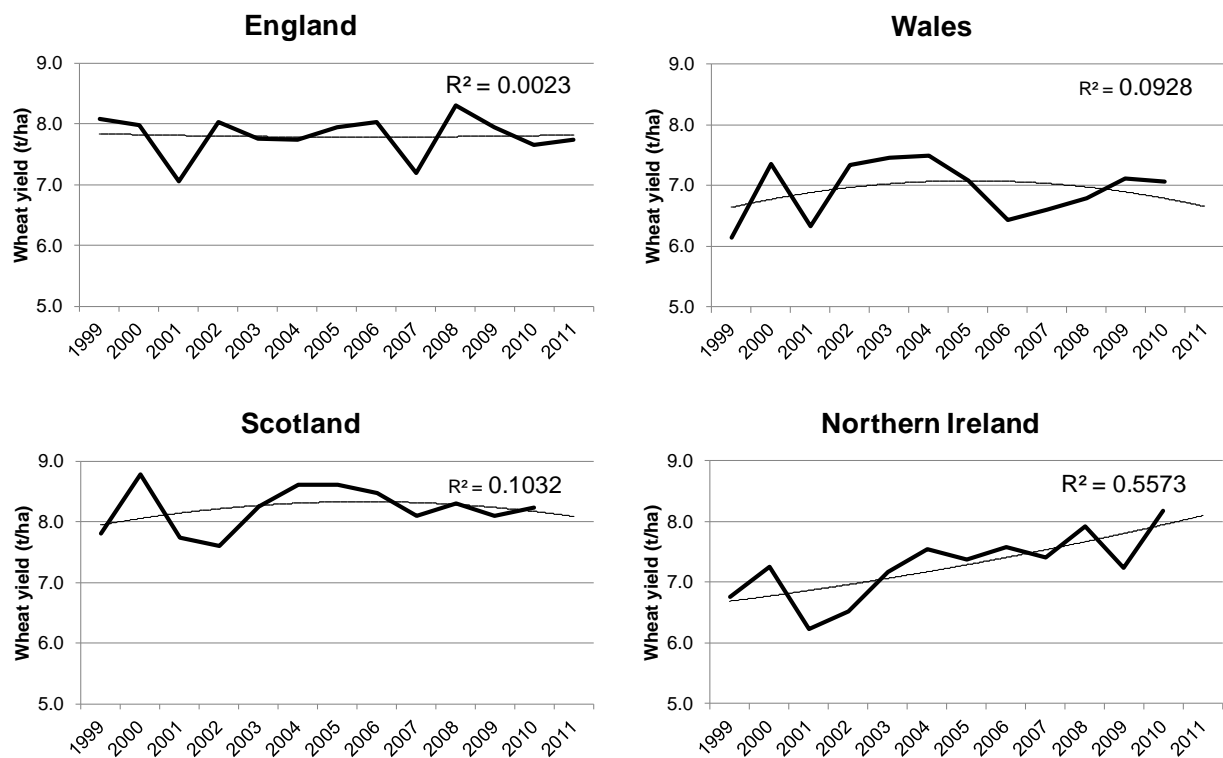


Figure 7. Wheat yield trends for England, Wales, Scotland and Northern Ireland from 1999 to 2011

Within the English regions there is great commonality, with the low yielding years of 2001 and 2007 reflected in all eight regions to varying degrees (Figure 8). Trend lines are generally quite flat, with the exception of the North East, which is more similar to Scotland with a period of better yields in the mid-2000s, and the North West and Merseyside, where an overall decline in yields is evident.

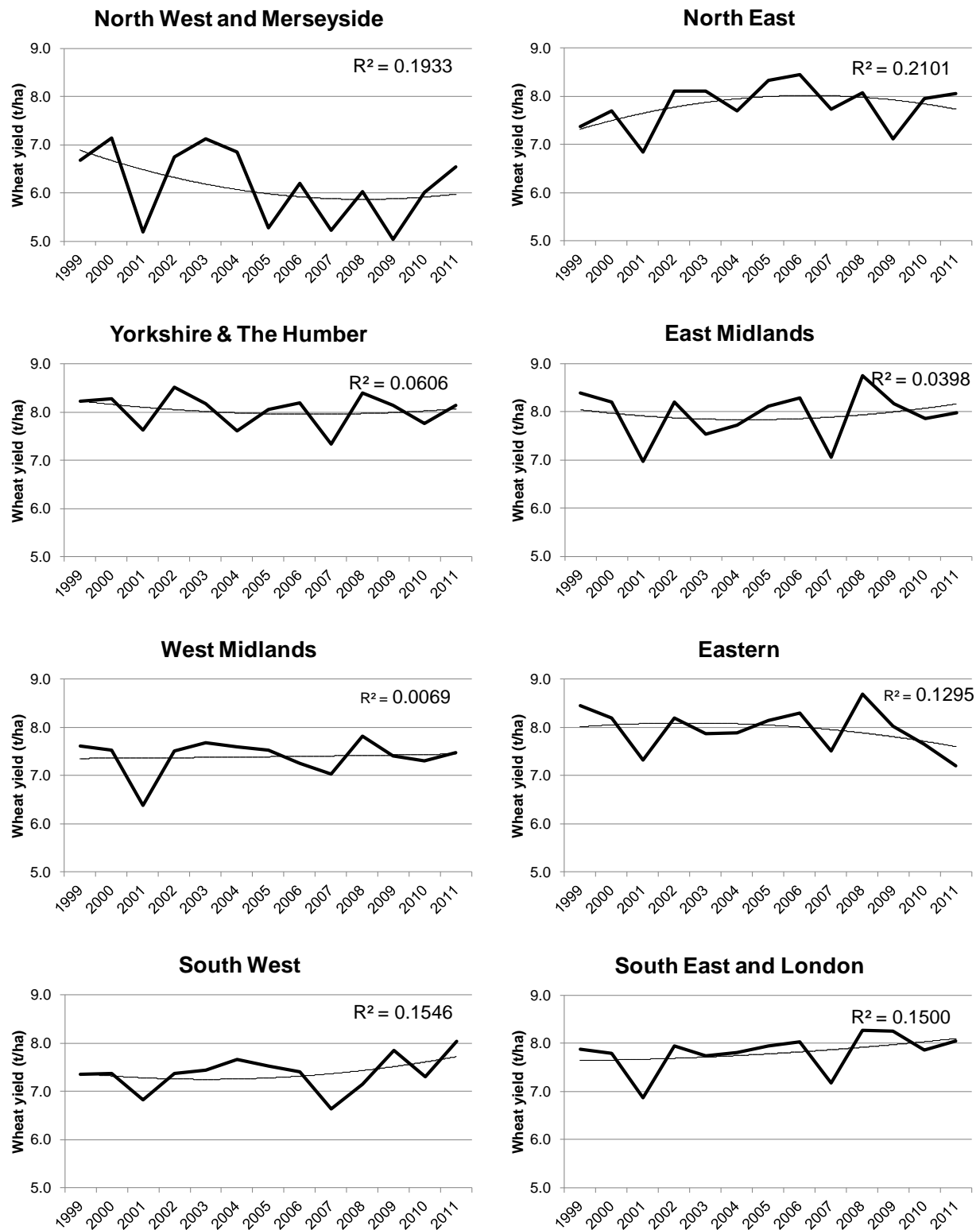


Figure 8. Wheat yield trends for English sub-regions from 1999 to 2011.

Differences between farms

Further insight into wheat yields is provided by Farm Business Survey data, based on about 800 farms per year for the period 1987-2009. Dividing the data into four yield quartiles indicates that while the bottom 25% appear to have plateaued in 2002 and gone into yield decline, this becomes less evident moving through the quartiles, with a suggestion that the top 25% have continued to increase slowly until 2007 (Figure 9). Examining the top and bottom quartiles it is evident that the gap between these two has increased, albeit erratically, by about 1.5 t/ha between 1987 and 2009 (Figure 10). However the % yield increase for each yield quartile is very similar over that time, such that the increasing yield gap is mainly a consequence of the higher starting point of the top quartile.

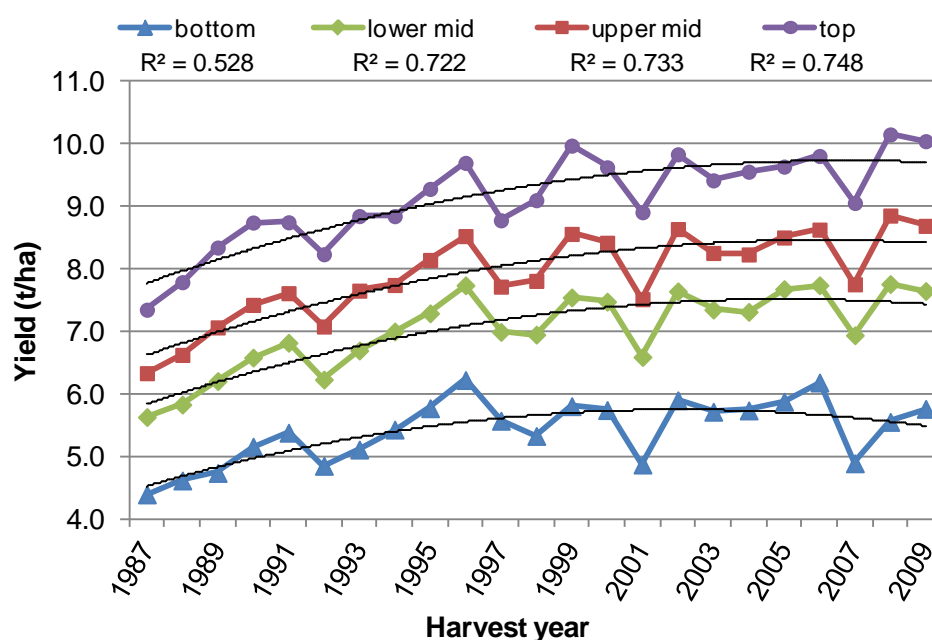


Figure 9. Wheat yield trends within Farm Business Survey yield quartiles

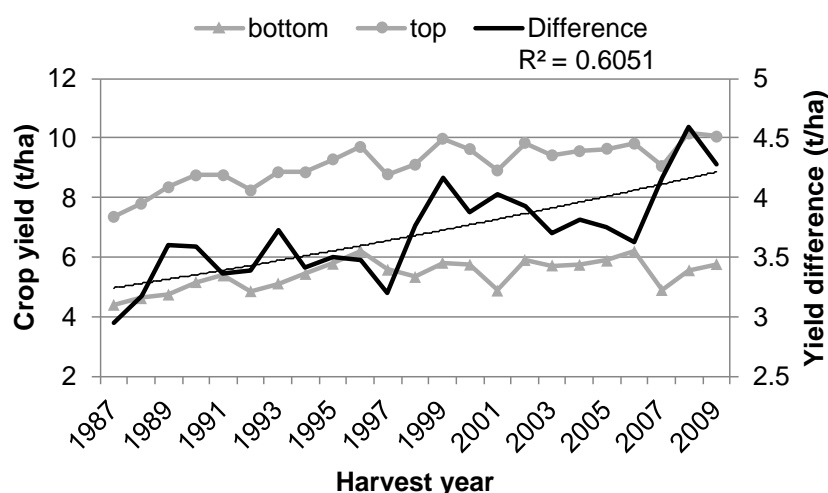


Figure 10. Annual difference between top and bottom wheat FBS yield quartiles

Dividing the data by wheat gross margin instead, it is evident that farms in the top quartile for gross margin from 2004 to 2009 have also achieved the highest mean yield, and farms in the bottom

quartile for gross margin have achieved the lowest yield (Figure 11). However, the yield gap between farms in the top and bottom gross margin quartiles has not changed over the six years.

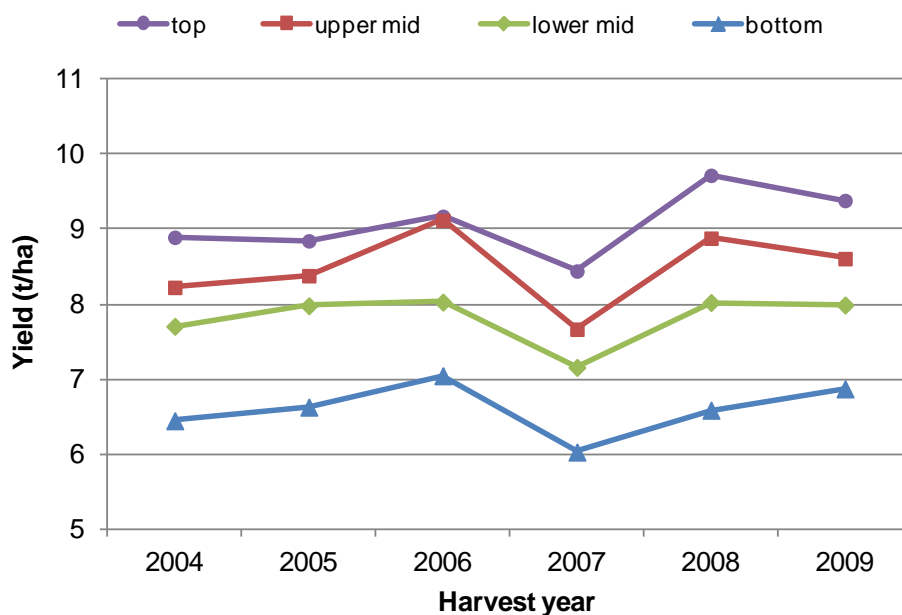


Figure 11. Recent wheat yield trends within FBS gross margin quartiles.

The Farm Business Survey also highlights the relationship between yield quartile and wheat crop area. From 2004 to 2009 the top yield quartile have grown the largest wheat area and the bottom yield quartile have grown the smallest wheat area, with the top yield quartile growing more than twice as much wheat as the bottom quartile (Figure 12). This may be because the latter farms are smaller, or because the wheat crop represents a smaller proportion of their farm enterprises. The relative areas for the top and bottom quartiles have changed very little over the period analysed.

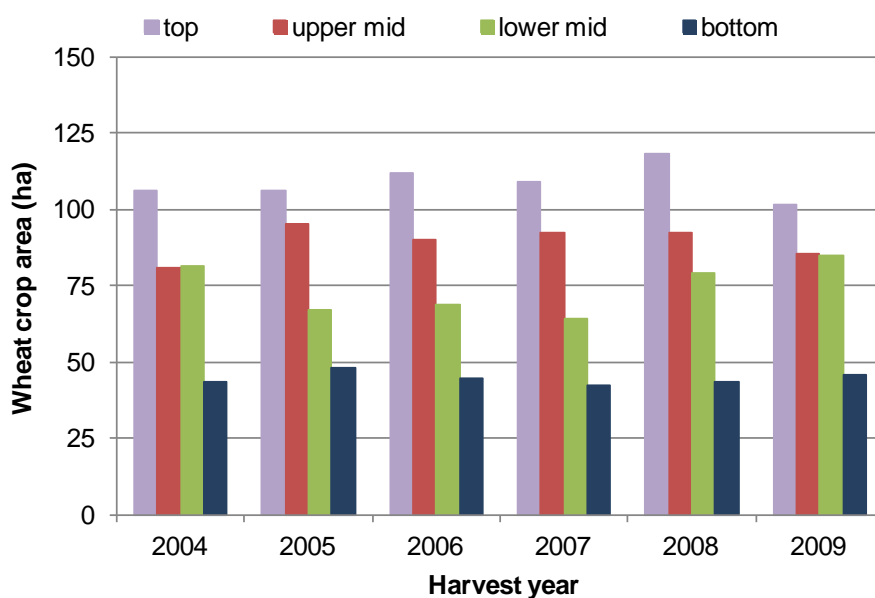


Figure 12. Mean area of wheat grown by FBS top, upper & lower middle and bottom yield quartiles.

Many of the twelve case study farms that were examined showed fairly weak farm average wheat yield trends since 1996. Overall examination did not highlight any specific individual agronomic factors associated with increasing or decreasing yields. A range of establishment, rotational and crop nutrition practices are being used on farms that are or aren't showing signs of improvement.

Table 1 shows the % change in yield and four key agronomic factors, when comparing the 5-year mean for 1996-2000 against the 5-year mean for 2006-2010, for ten farms for which a full dataset was available back to 1996. The four agronomic factors were the proportion of the wheat crop area sown following wheat, the proportion of the wheat crop area ploughed, the proportion of the wheat crop area sown in September and the total (inorganic) fertiliser N dose applied. On two farms (N3 and Y1) up to 30% of the wheat area had started to receive organic manures since 2000.

Table 1. % change in wheat yield and four agronomic factors for 10 case study farms, when comparing their five year averages for 1996-2000 and 2006-2010.

Case study farm	N2	L1	N3	D2	A3	D1	Y1	K1	A2	N1
% increase (+) or decrease (-) in yield, area or N dose										
Average farm wheat yield	-8	-4	-1	+2	+3	+3	+4	+7	+12	+18
Proportion following wheat	-38	-41	-6	-14	-10	-9	-16	-37	0	-25
Proportion ploughed	-12	0	+6	-100	0	-96	-16	-100	0	-80
Proportion sown in Sept	+12	+17	-14	-2	0	+6	+19	+50	n/a	+47
Total N fertiliser dose	-3	-7	-16	0	+11	+8	+7	0	0	+4

On three of the twelve farms there were signs of rising yield trends, of about 0.1-0.15 t/ha per year, although with considerable variation still throughout this period (Figure 13).

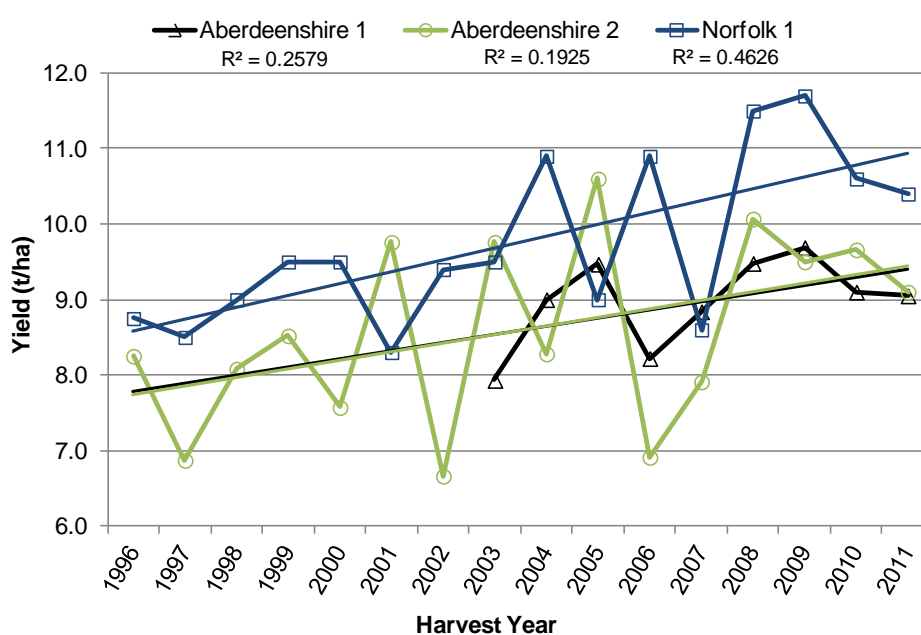


Figure 13. Recent winter wheat average yield trends for three case study farms in the UK (trends for Aberdeenshire 1 and 2 lie on the same line).

Key features of the three case study farms illustrated in Figure 13 above are as follows:

Aberdeenshire 1 (farm size c. 220ha, medium soil and growing 30-50ha of winter wheat):

- All first wheat following oilseed rape until 2008; 50-100% following other cereals since then;
- 20% group 1/2 varieties since 2007; 100% group 3/4 before then;
- 100% ploughed;
- 100% sown after the end of September (except 2003 and 2007);
- Slightly below-average N fertiliser use (160-200 kg N/ha), but some organic manure used;
- 75-100% of the crop receiving S fertiliser since 2004.

Aberdeenshire 2 (farm size c. 1200ha, medium soil and growing 30-70ha of winter wheat):

- All first wheat, main preceding crops oilseed rape and (in some years) potatoes;
- 100% group 3/4 varieties;
- 100% ploughed;
- Predominately September sown;
- Average N fertiliser use (200 kg N/ha);
- 100% of the crop receiving S fertiliser since 2003.

Norfolk 3 (farm size c. 2100ha, medium & deep clay soils and growing 600-750ha of winter wheat):

- All first wheat since 2004, 15-25% second or subsequent wheats before then;
- Main preceding crops now pulses and sugar beet, plus oilseed rape since 2002;
- 100% group 3/4 varieties since 2003, 15% group 1/2 varieties before then;
- 80% deep non-inversion since 2003, 100% ploughed before then;
- 90% sown by the end of September since 2003, only 40-50% before 2003;
- Above-average N fertiliser use (220-250 kg N/ha);
- 100% of the crop receiving S fertiliser since 1996.

All three of these case study farms have taken steps during the 2000s in order to raise productivity, for example altering rotations, nutrient mapping, avoiding soil compaction and increased attention to detail in terms of crop and soil management, including the application of S fertiliser.

3.4.3. Trends in grain quality

Data from the HGCA Cereal Quality Survey show significant year to year variation in the mean wheat grain specific weight for Great Britain, especially from the mid-1980s to 1990s (Figure 14). Very little trend over time is evident. The picture is similar for Hagberg Falling Number (Figure 15),

but with a brief dip in values during the mid-1980s. No pattern is apparent for either quality attribute that bears any resemblance to the national yield trend (Figure 4) over the same period.

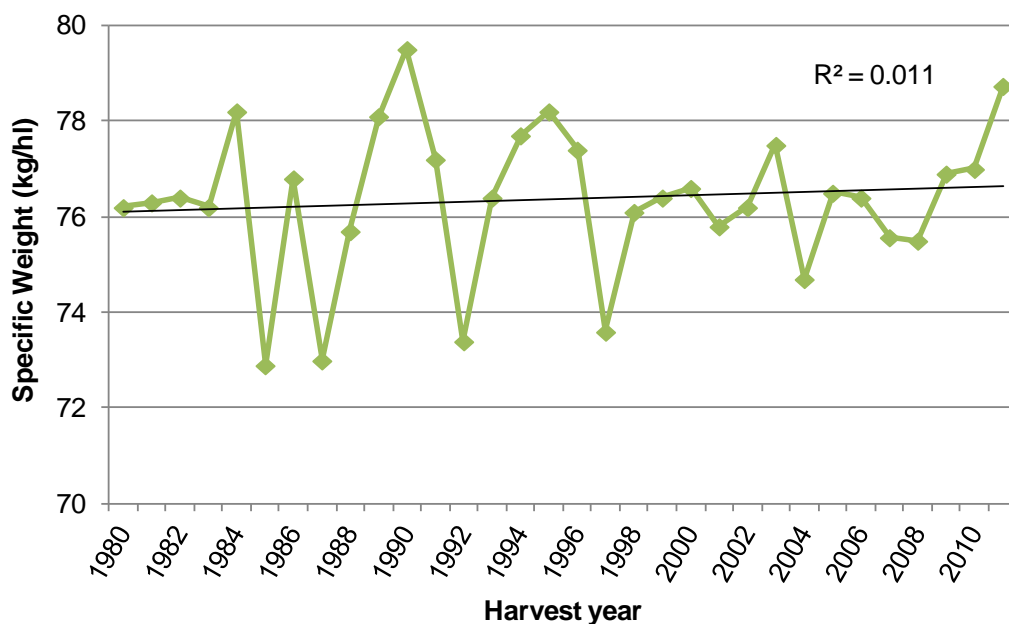


Figure 14. Average wheat grain specific weights for Great Britain from 1980 to 2011.

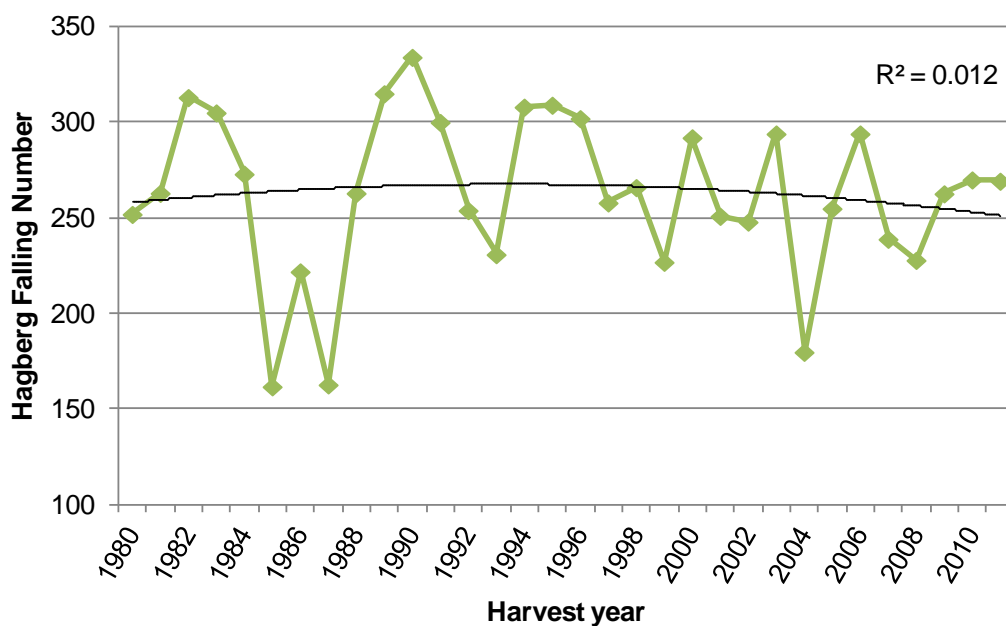


Figure 15. Average wheat grain Hagberg Falling Number for Great Britain from 1980 to 2011.

Trends in wheat grain % protein content are complicated by the change in moisture content (to 0% moisture or 100% dry matter) at which proteins were recorded after 1998, which results in a step change in the data. The two time periods are therefore shown separately in Figure 16. There is an indication of a slight downward trend in grain protein content between the 1980s and 1990s, which would be consistent with rising national yields (Figure 4) and static rates of N fertiliser application (described later in Section 3.4.8 and Figure 44).

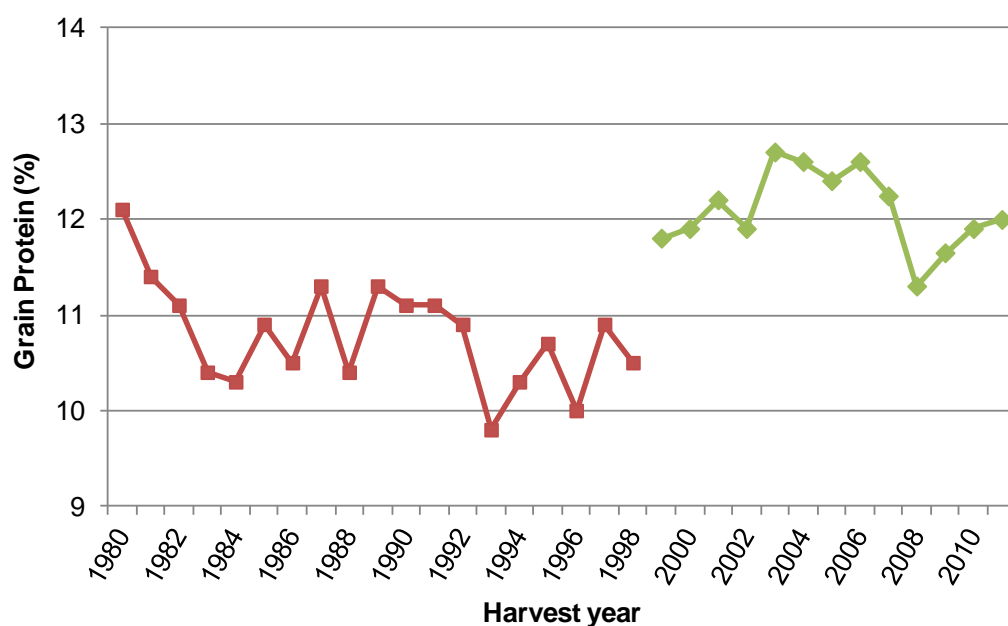


Figure 16. Average wheat grain protein content (%) for Great Britain from 1980 to 1998 (at 14% moisture content) and from 1999 to 2011 (at 0% moisture content).

3.4.4. Genetics and yield potential

Quantifying the contribution of genetics to the UK yield trend is an important step, and this will depend on both rate of variety improvement and the uptake of higher-yielding varieties on farm. A new analysis of NIAB Classified List data, a composite of NL and RL trials data for varieties on the current NL of winter wheat, has identified the varieties (Appendix Table 2) in each of the nabim Groups that have contributed to genetic improvement in yield potential (Figure 17) based on their lifetime trial mean yields. The annual yield improvement has ranged from 0.039 t/ha for Group 3 varieties to 0.097 t/ha for Group 4 varieties, with Group 1 and 2 varieties intermediate. The average across all Groups is 0.063 t/ha per year, equating to a potential yield gain on farm of about 0.050 t/ha per year.

In a second exercise, seed certification data since 1990 were analysed and a yield trend projected, assuming that the varieties were grown in proportion to the quantities certified and based on their yields in trials. Variation in nabim Groups with time, as indicated by certification data, is shown in Figure 18. The use of final weights certified to indicate area grown is somewhat speculative as it does not account for farm saved seed. In addition, the final weights certified, while partly reflecting confidence in the variety in the year of seed production, are also indicative of seed available for the following season. Varieties performing poorly on farm or in trials in the year of seed production have a reduced likelihood of achieving target sales for the following season. Nevertheless for the purpose of projecting a theoretical yield trend over time, this is considered a satisfactory proxy.

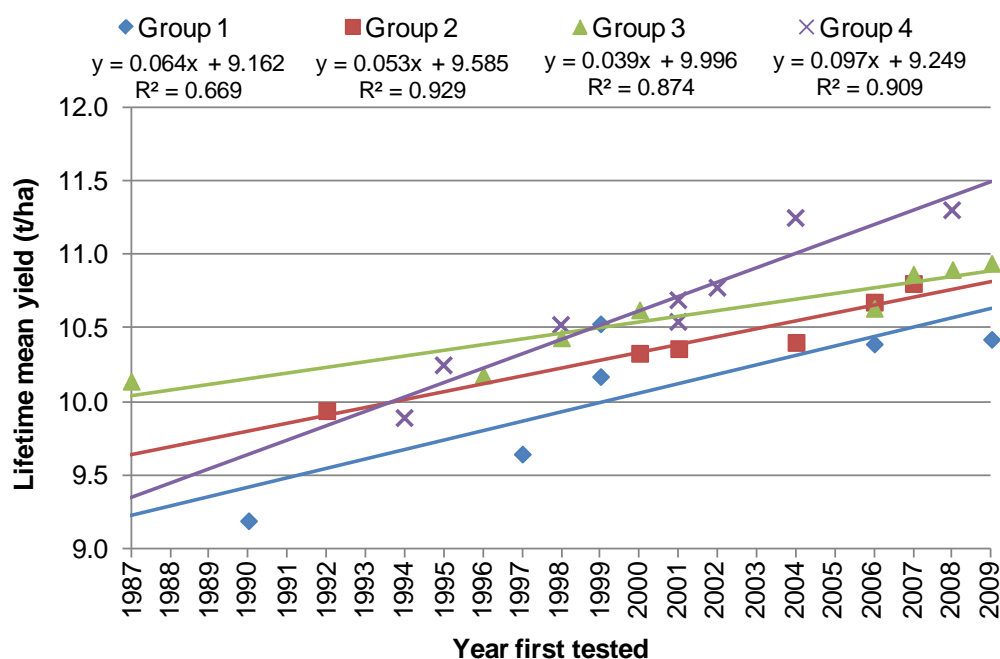


Figure 17. Genetic yield improvement within winter wheat nabim Groups ($x = 1$ for 1987).

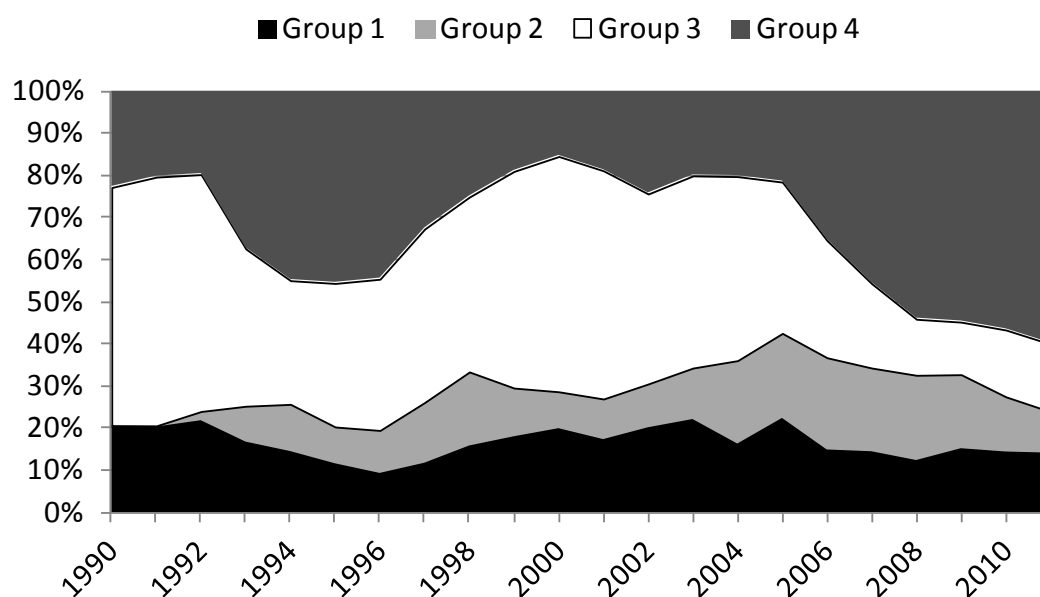


Figure 18. Annual variation in wheat seed certification final weights – contributions by nabim Group

Two approaches were used. For the first, 'lifetime' yield averages for the 1990 to 2011 period were used for each variety, calculated using a two-stage fitted constant analysis. This removes the effect of annual variation due to weather or other influences. Annual mean yield (Y) is estimated where:

$$Y = \left(\frac{\% \text{ of seed for individual variety}}{\% \text{ of seed accounted for by all varieties included in that year}} \right) \times \text{'life time' average yield for that variety}$$

For the second approach, individual trial records are used for varieties, where they exist, in order to examine the yield trend annual variation due to weather or other influences. Here:

$Y = (\% \text{ of seed for individual variety divided by total \% of seed accounted for by all varieties included in that year}) \times \text{trial yield for that variety in that year}$

The results of this exercise are presented in Figure 19. The slope of the trend line for projected national yield based on 'life time' mean yields indicates a potential yield improvement averaging about 0.06 t/ha per year. As trials yields are typically about 20% higher than commercial yields, due to a number of factors associated with plot size and site selection, this analysis would also equate to a potential for average yield improvement on farm of about 0.05 t/ha per year. Closer examination of the data indicates a slightly slower rate of yield improvement for the period from about 1996 to 2005, compared to either 1990 to 1996 or 2005 to 2011. This is associated with a slight increase in the proportion of Group 1 or 2 varieties being grown, and a decrease in the proportion of Group 4 varieties. It is estimated that this could account for a loss of potential yield improvement of about 0.01 t/ha per year during the 1996 to 2005 period.

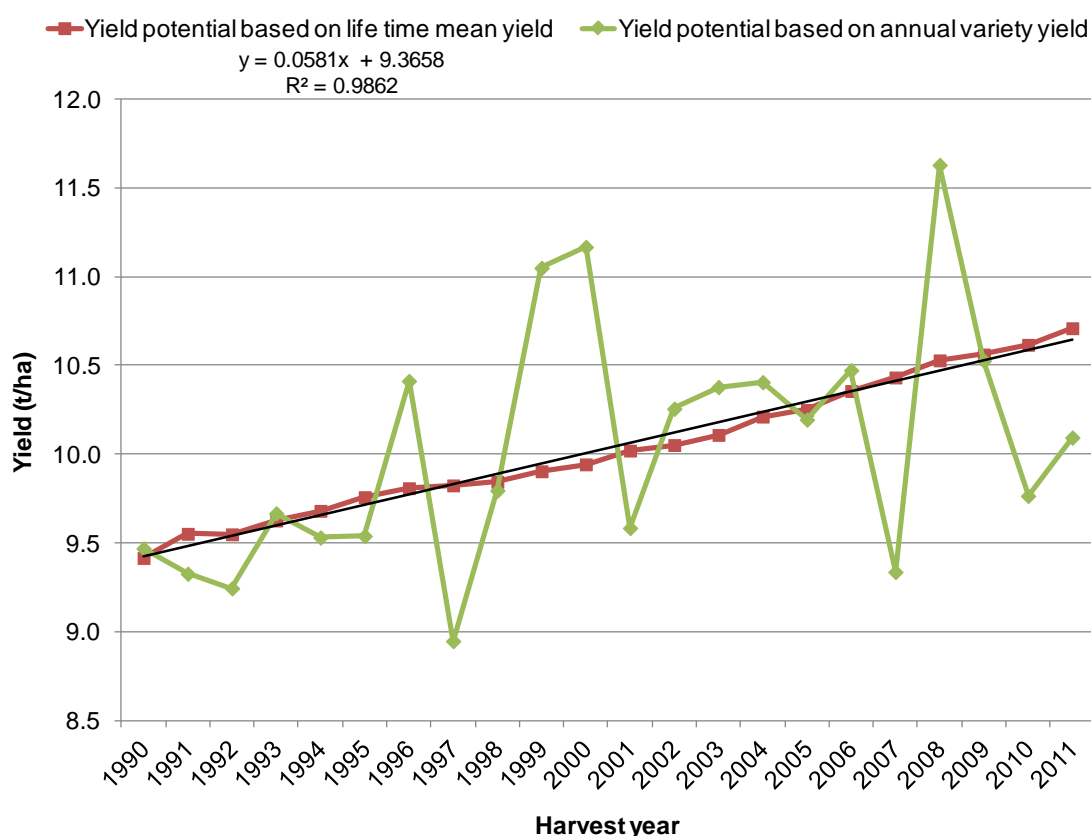


Figure 19. Projected national yield trend for wheat based on annual seed certification and yields observed in variety trials (linear trend line fitted to yield potential based on life time mean yield, $x=1$ for 1990; $P < 0.001$; SE slope 0.0015, intercept 0.0202).

Data from the Farm Business Survey reveal no differences in average farm expenditure on wheat seed between any of the yield quartiles, with all showing a slight upward trend in recent years.

Mycorrhiza

It is known that wheat plant roots can form symbiotic associations with arbuscular mycorrhizal fungi (AMF). The benefits of this can include improved nutrient transfer from soil to plant, better soil structure (through soil aggregation) and increased resistance to drought or soil-borne pests (including root nematodes) and root-infecting fungal diseases (Gosling *et al.*, 2006). These are achieved by growth of the fungal mycelium within a host root and out into the surrounding soil. High inputs of inorganic fertilisers (especially phosphates and nitrates), certain fungicides and soil sterilants, soil disturbance during tillage and the growing of non-mycorrhizal hosts e.g. oilseed rape and sugar beet can have negative effects on AMF. Studies have also demonstrated a strong genetic basis for differences in mycorrhizal dependence among wheat varieties (Hetrick *et al.*, 1992). However, it is not at this stage known whether or not any changes have occurred in AMF associations with wheat since 1980 that could have an impact on crop performance.

3.4.5. Climate and weather

The evaluation of possible climate or weather impacts on yields from 1980 to 2011 included:

1. An examination of seasonal weather trends for the UK as a whole, to highlight the key changes over time;
2. An analysis of correlations between de-trended UK yields and individual monthly mean weather variables for the UK and separately for England, in order to identify weather variables that may be associated with annual yield variation. It is noted that with the large number of variables involved there is a possibility of generating spurious statistically significant correlations;
3. A comparison of trends in specific monthly mean weather variables for England with the UK yield trend;
4. A multivariate analysis to look at the combination of weather factors that may be important.

Seasonal weather trends from 1980 to 2011

Trends in mean UK seasonal maximum and minimum temperatures, total rainfall and sunshine hours are presented in figures 20 to 23. The period from 1980 to 2011 has seen rising maximum and minimum temperatures, notably in autumn and spring, with a 2°C increase in average spring maximum temperature over the three decades. There has been much variation in rainfall, but very little trend in any season, and some increase in sunshine hours particularly in spring.

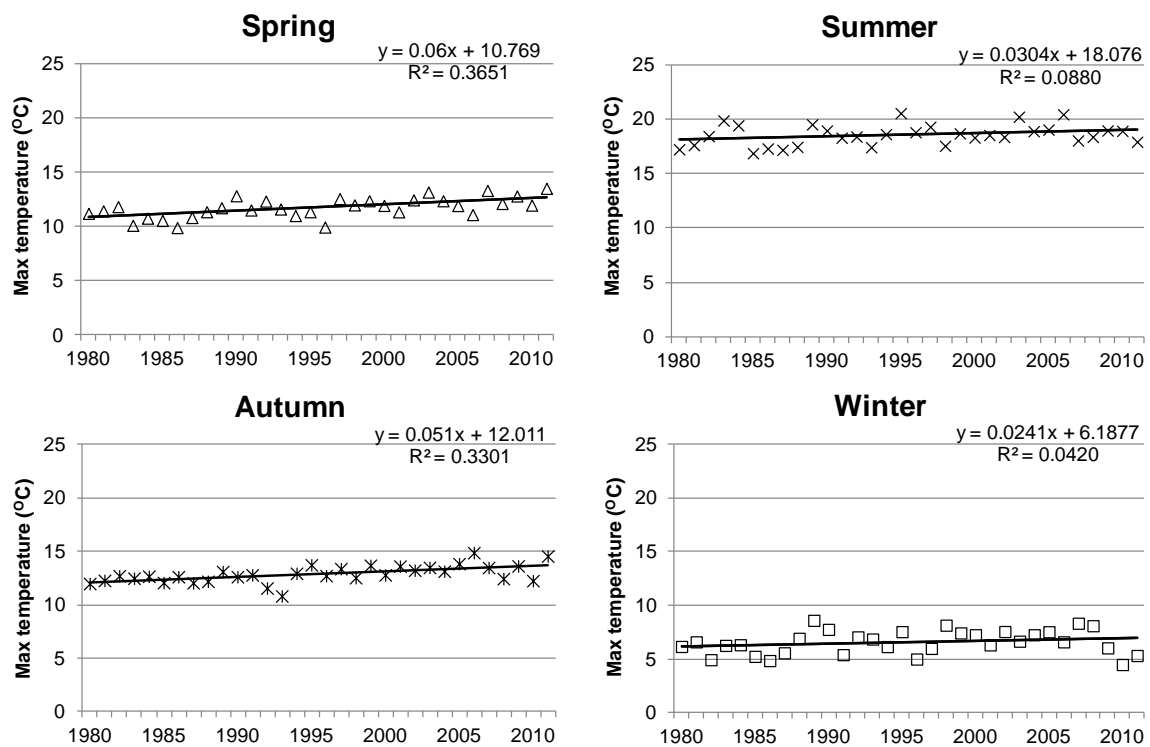


Figure 20. UK mean seasonal maximum temperatures ($^{\circ}\text{C}$) 1980 – 2011 ($x=1$ for 1980).

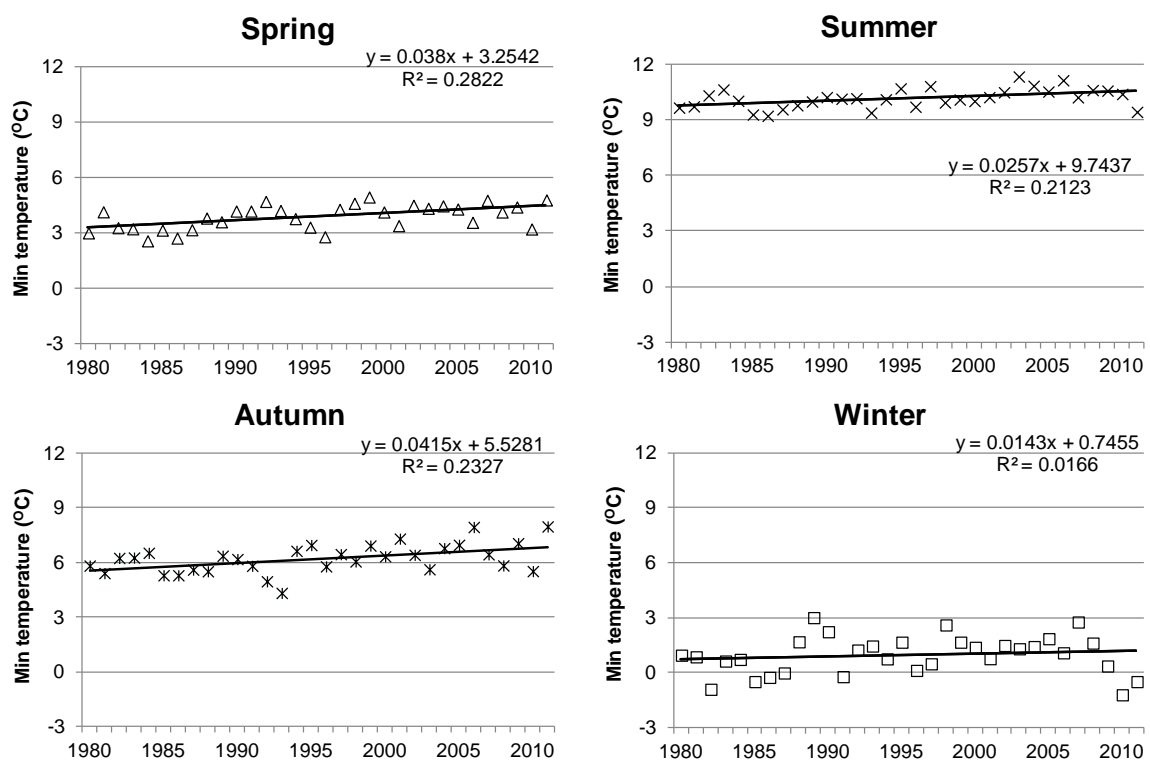


Figure 21. UK mean seasonal minimum temperatures ($^{\circ}\text{C}$) 1980 – 2011 ($x=1$ for 1980).

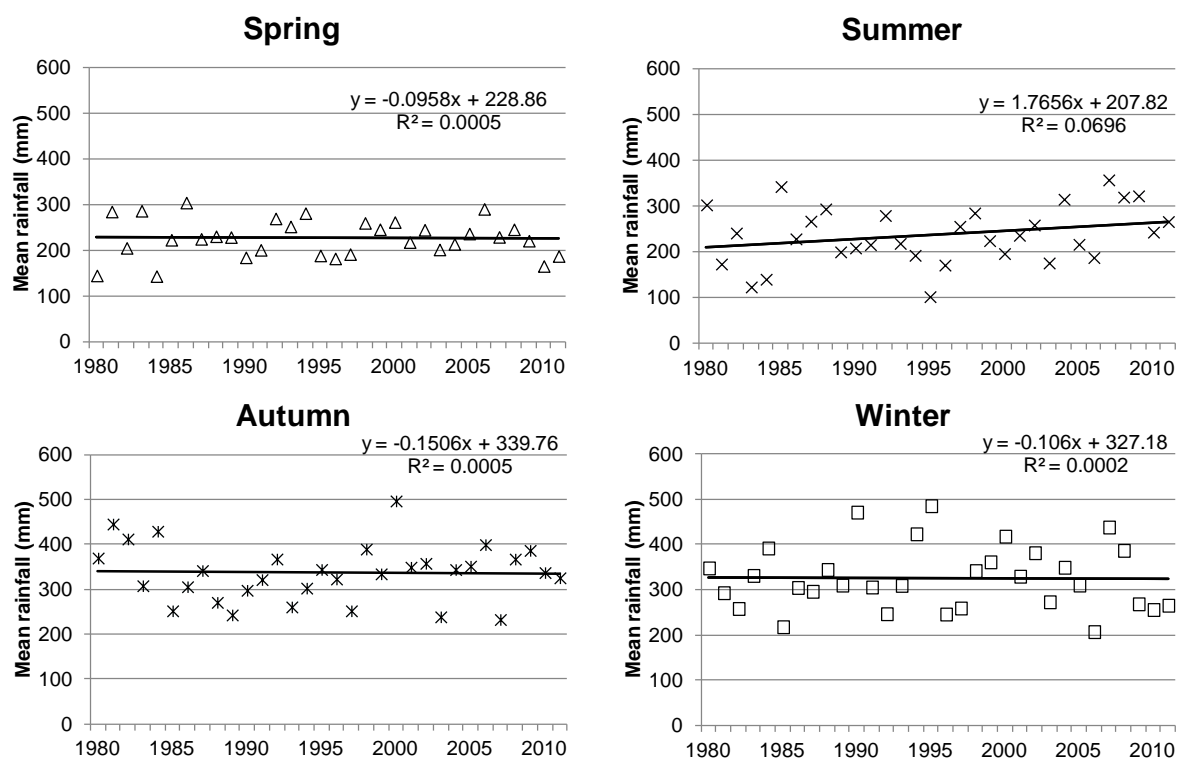


Figure 22. UK mean seasonal rainfall totals (mm) 1980 – 2011 ($x=1$ for 1980).

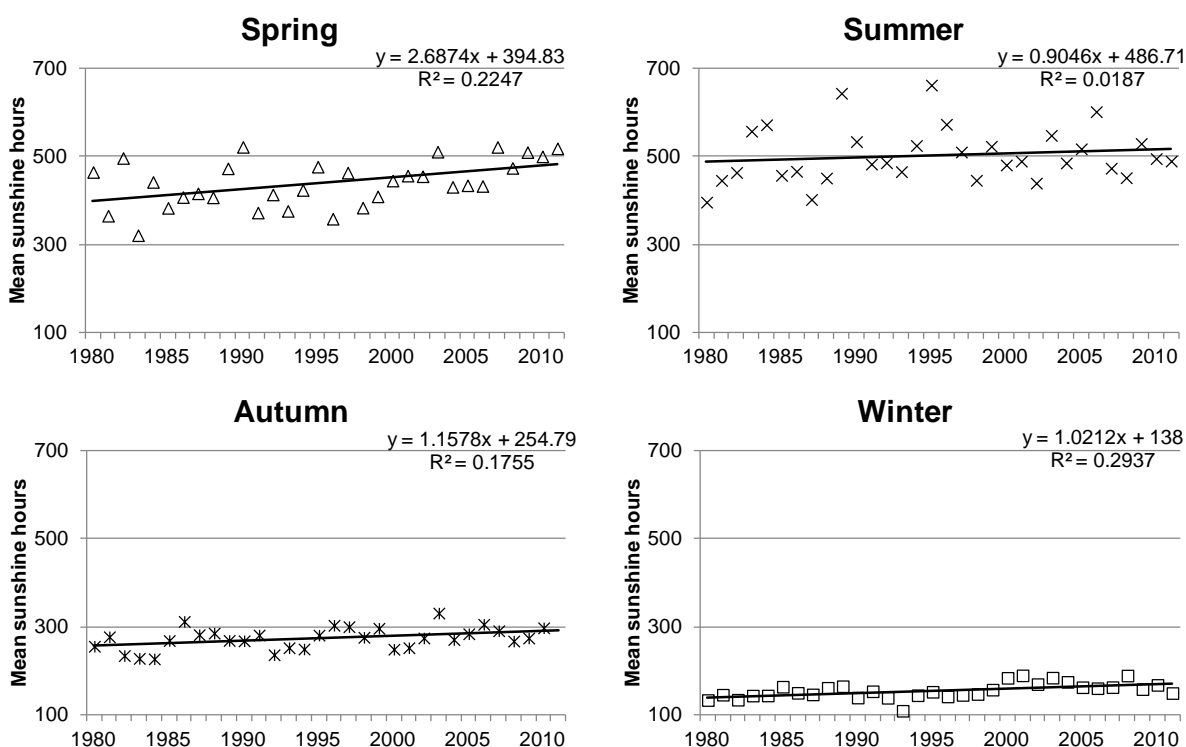


Figure 23. UK mean seasonal sunshine hours total (hours) 1980 – 2011 ($x=1$ for 1980).

Monthly mean weather variables

Correlations between de-trended UK wheat yields and individual UK monthly mean weather variables were examined for the 'harvest' years from 1980 to 2011 (Table 2). Each harvest year ends in August and includes September to December of the previous year. As the majority of the

wheat crop is grown in England, UK yield correlations with monthly mean weather variables for England have been examined for the same period (Table 3). Monthly data for England has been used to illustrate trends in specific weather variables from 1980 to 2011 in Figures 24 and 27-31.

Table 2. National wheat yield correlations with UK weather, and significance levels, 1980 to 2011.

UK	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
Rainfall	-0.217	0.007	0.116	-0.200	0.057	0.252	-0.447	0.286	0.205	-0.015	0.273	0.080
Sunshine	0.150	0.246	0.291	0.445	0.154	0.309	0.396	0.163	0.194	0.314	0.046	0.065
Mean Temp	0.361	0.287	0.241	-0.116	0.308	0.343	0.337	0.444	0.402	0.400	0.170	0.252
Max Temp	0.381	0.328	0.288	-0.081	0.300	0.379	0.425	0.393	0.327	0.423	0.136	0.209
Min Temp	0.321	0.241	0.182	-0.111	0.324	0.308	0.216	0.521	0.458	0.369	0.264	0.320
Significance Levels	5% +ve 5% -ve		+ve -ve	0.349 -0.349		1% 1%	+ve -ve	0.449 -0.449				

Monthly rainfall interactions and trends

From 1980 to 2011 there is an apparent negative correlation between national yield and March rainfall for the UK as a whole and for England, but investigation has shown that this is the result of a few atypical years in the early 1980s, and if these are excluded there is no recent correlation.

Table 3. National wheat yield correlations with weather for England, and significance, 1980 to 2011

England	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
Rainfall	0.001	0.040	0.200	-0.141	0.014	0.224	-0.467	0.084	0.062	-0.100	0.290	0.126
Sunshine	0.046	0.207	0.257	0.286	0.057	0.315	0.375	0.196	0.181	0.340	0.074	0.022
Mean Temp	0.289	0.292	0.220	-0.110	0.295	0.378	0.324	0.493	0.463	0.455	0.196	0.273
Max Temp	0.255	0.306	0.266	-0.111	0.263	0.390	0.403	0.439	0.391	0.468	0.135	0.203
Min Temp	0.278	0.262	0.164	-0.101	0.318	0.353	0.210	0.527	0.523	0.376	0.263	0.349
Significance Levels	5% +ve 5% -ve		+ve -ve	0.349 -0.349		1% 1%	+ve -ve	0.449 -0.449				

April rainfall for England shows an increasing trend from 1980 to the mid-1990s and then a decreasing trend up to 2011, but with no linear relationship to yield evident (Figure 24).

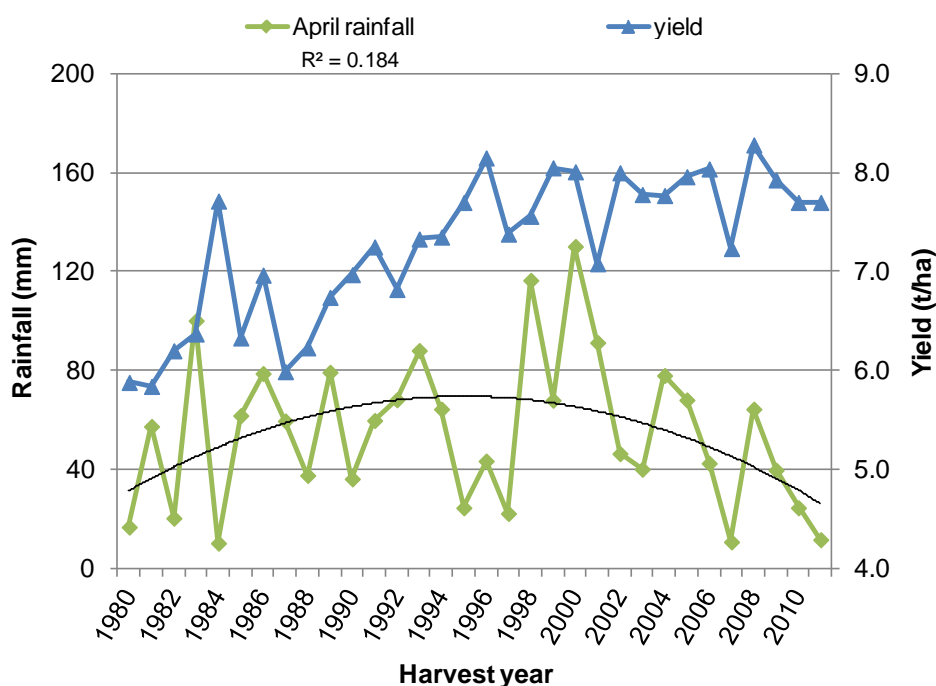
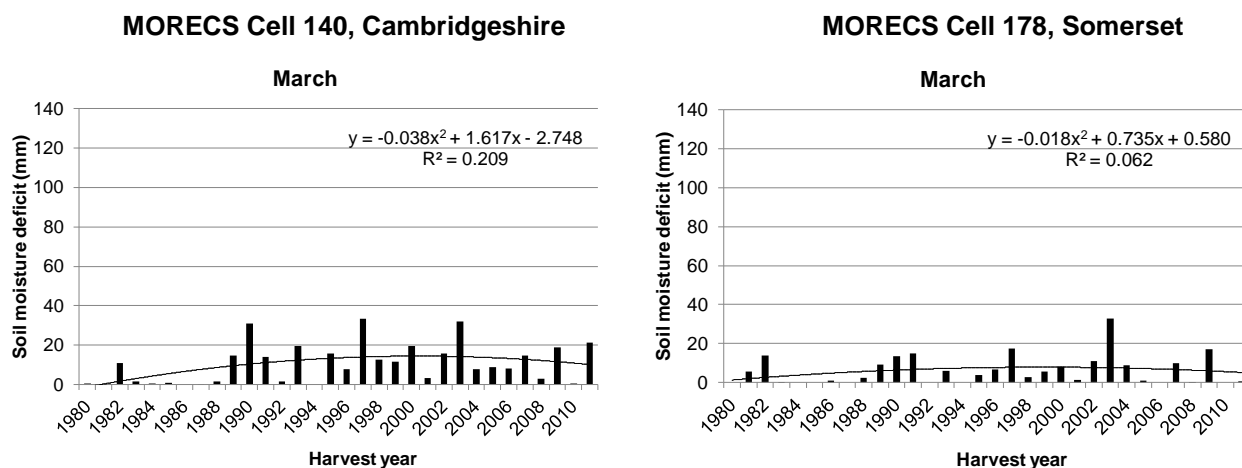


Figure 24. Trends for UK average wheat yield and April rainfall for England.

Monthly soil moisture deficit interactions and trends

While no positive correlations between rainfall and yield were found, this does not necessarily mean that available moisture has not affected yields. MORECS data for soil moisture deficit (SMD) were obtained for two 40km square 'cells' in areas that grow a significant area of wheat, one in the drier east (cell 140 covering part of Cambridgeshire) and the other in the higher rainfall west of England (cell 178 covering part of Somerset). Correlations for monthly mean SMD data and UK average wheat yields are presented in Table 4. Two significant positive correlations are apparent for Cambridgeshire, in March and June. This is surprising, but for June can be explained by the yield correlation with sunshine hours (associated with lower rainfall) described later. Monthly SMD estimates for the March to June period are presented in Figure 25 for the two cells.



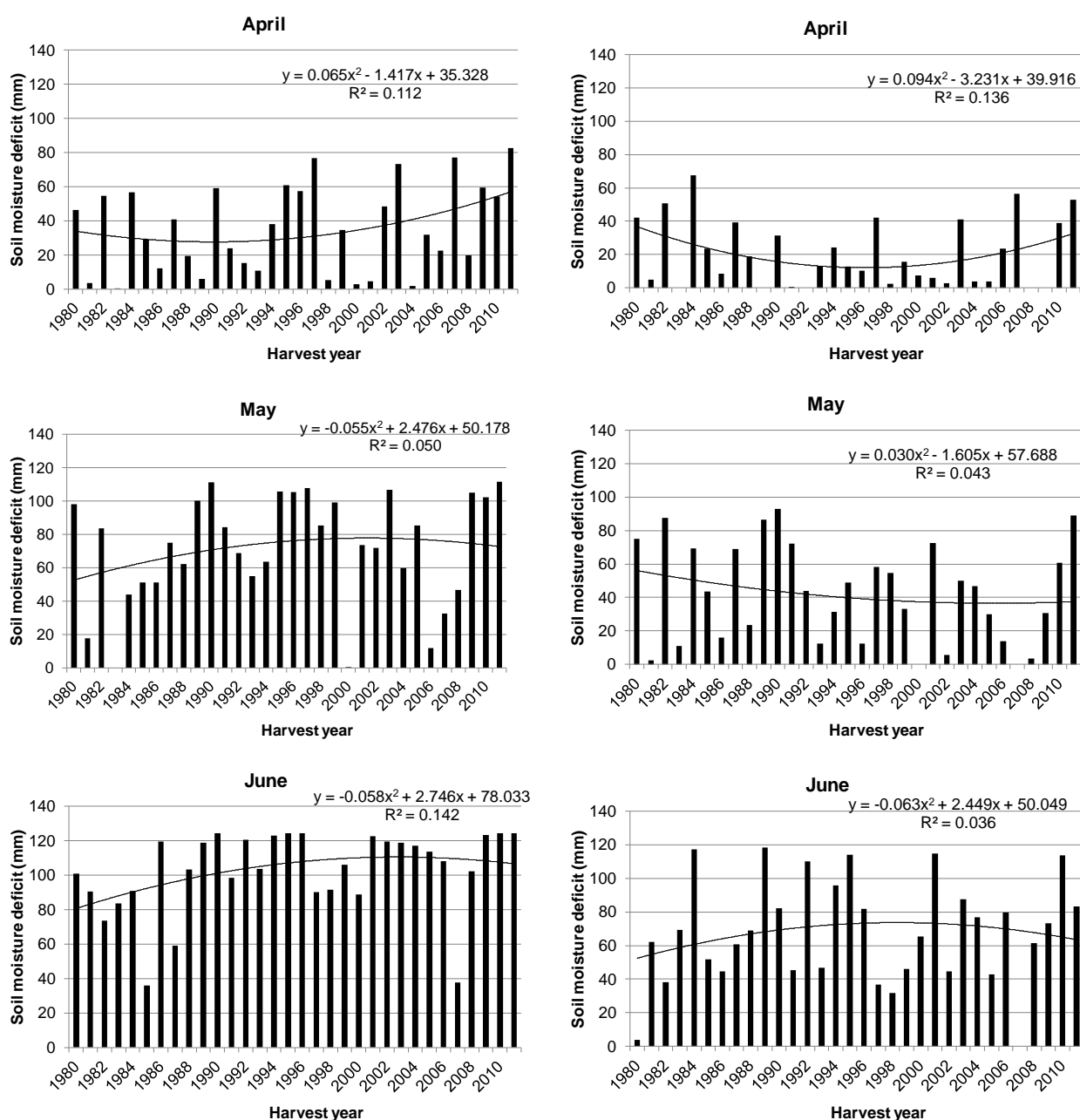


Figure 25. Monthly SMD estimates for March to June from 1980 to 2011 for MORECS cells in Cambridgeshire and Somerset.

Table 4. National wheat yield correlations with monthly soil moisture deficits from 1980 to 2011.

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	Jul	Oct
Cell 140	-0.140	0.010	-0.028	-0.084	0.040	-0.037	0.365	0.213	0.143	0.441	0.325	-0.044
Cell 178	0.141	0.119	-0.160	0.033	0.065	-0.142	0.172	-0.143	-0.265	0.191	0.067	0.064

Patterns over time are weak, as indicated by the low R^2 values of trend lines fitted to the monthly data, which were only significant for March and June for Cambridgeshire and April for Somerset. Both April trend lines show an apparent change in direction in the mid-1990s, from a decreasing to an increasing SMD. The June trend line for Cambridgeshire indicates an increasing incidence of higher SMDs over the last 30 years but with lower SMDs from 1997 to 2000 and in 2007

Applying the same SMD data to the shorter 1999 to 2011 set of Defra yield data for the east of England shows a more logical negative relationship between yield and SMD from March to June, and especially in April, although none of these were significant (Table 5). Examination of the June data in greater detail (Figure 26) shows that, after a low SMD / high yield in 2008, the recent three high June SMDs in succession has been associated with a falling yield trend. A low SMD in 2007 was associated with a low yield but can be explained by other overriding weather influences.

Table 5. Correlation coefficients and significance levels for wheat yields and soil moisture deficit for the East of England from 1999 to 2011.

Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
-0.061	0.012	0.301	0.264	0.179	0.347	-0.128	-0.405	-0.32	-0.017	0.201	0.002
NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

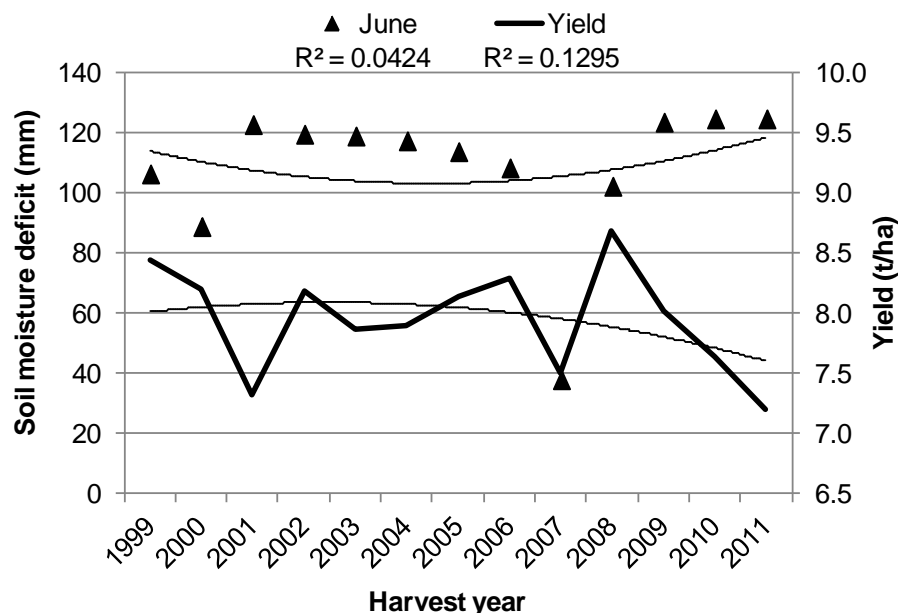


Figure 26. Soil moisture deficit and wheat yield trends for the East of England from 1999 to 2011.

Monthly sunshine hours interactions and trends

For the period from 1980 to 2011, significant positive correlations are apparent between national yield and sunshine hours for December and March for the UK. For England, sunshine hours in March show a rising trend since 1980. For the critical grain fill month of June, a near-significant positive yield correlation with sunshine hours is evident for England (Table 2). Higher June sunshine hours have coincided with yield spikes in 1984, 1986 and 1996 and yield dips in 1987 and 2007 (Figure 27).

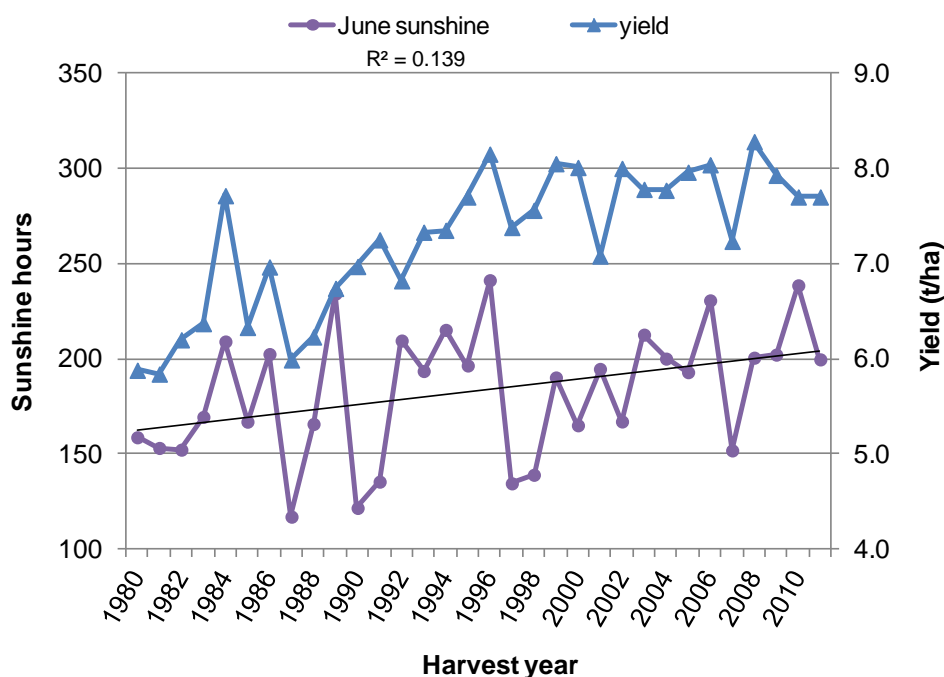


Figure 27. Trends for UK average wheat yield and June sunshine hours for England.

Monthly minimum temperature interactions and trends

From 1980 to 2011 there are significant national yield correlations with minimum temperatures for April, May and June for England and for the UK as a whole. For England, May and June minimum temperatures show an increasing trend since 1980 (Figure 28). January minimum temperatures for England show a variable but rising trend between 1980 and the early 2000s (Figure 29). Number of frost days per month was analysed from 1980 to 2011 (Table 6). Significant negative correlations were observed for September and January. The incidence of frosts shows no trend for September but for January there is evidence of a trend over time (Figure 30), and an indication that relatively cold Januarys may have contributed to a yield downturn in recent years.

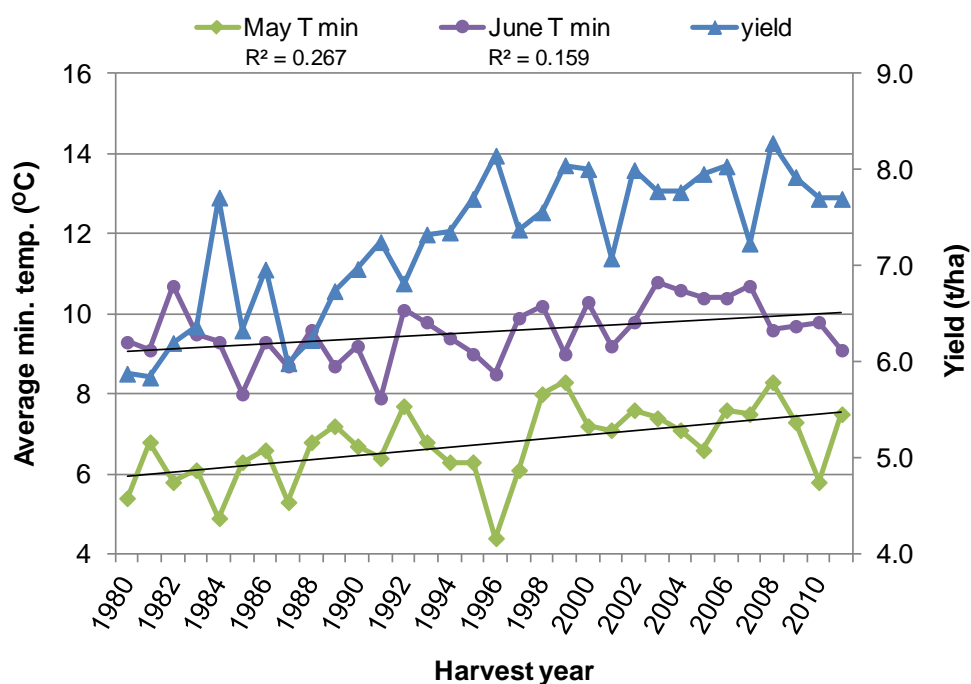


Figure 28. Trends for UK average wheat yield and May and June minimum temperatures for England.

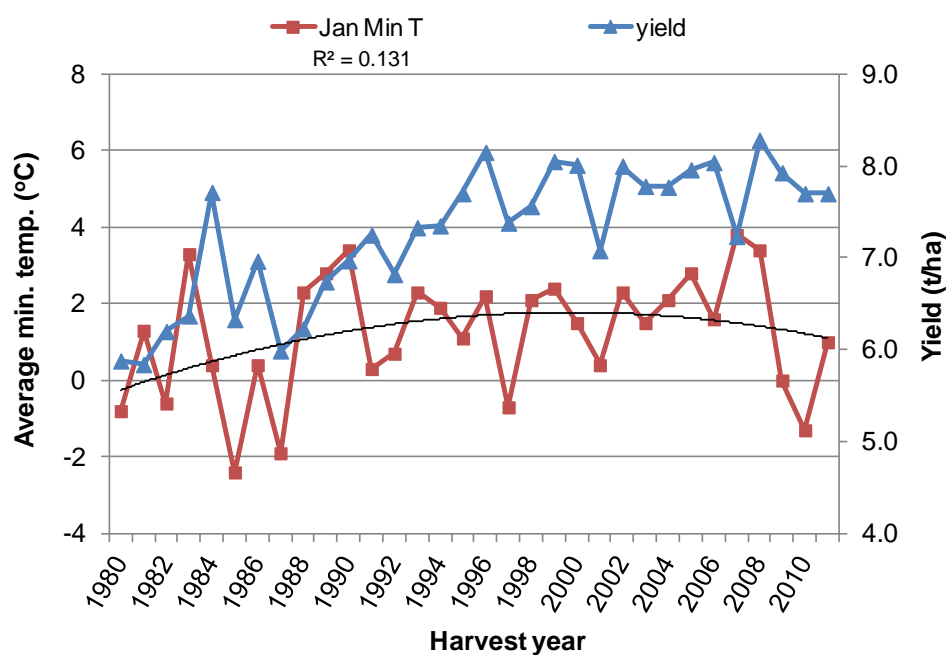


Figure 29. Trends for UK average wheat yield and January minimum temperature for England.

Table 6. Average number of frost days for England and correlation with UK wheat yields, 1980 - 2011.

England	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
Frost days	0.1	1.4	5.1	10.1	10.7	10.3	6.5	3.5	0.7	0.0	0.0	0.0
Correlation	-0.384	-0.036	-0.005	0.191	-0.356	-0.164	-0.070	0.009	-0.005	-0.112	-	-

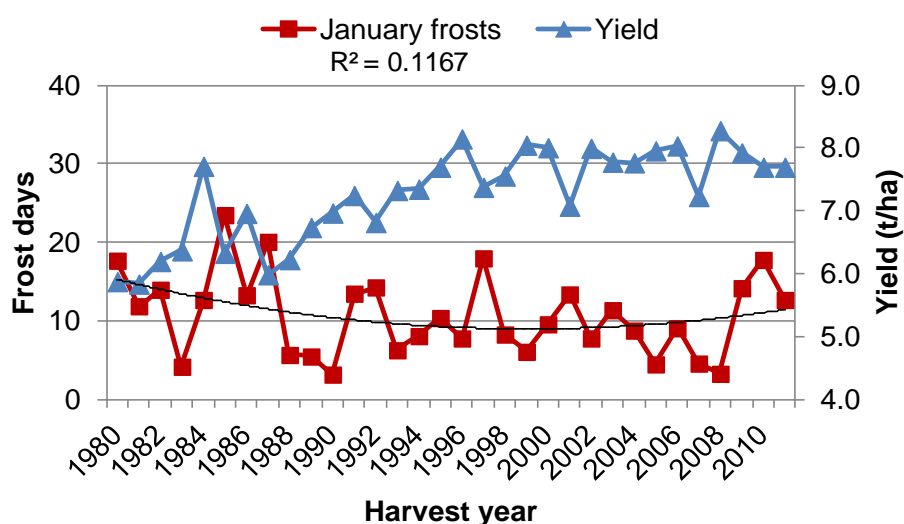


Figure 30. Trends for UK average wheat yield and number of frost days in January for England.

Monthly maximum temperature interactions and trends.

Significant correlations between national yields and monthly maximum temperatures for England and the UK as a whole are evident between February and June. For England, there has been a clear rising trend in June maximum temperatures since 1980 (Figure 31).

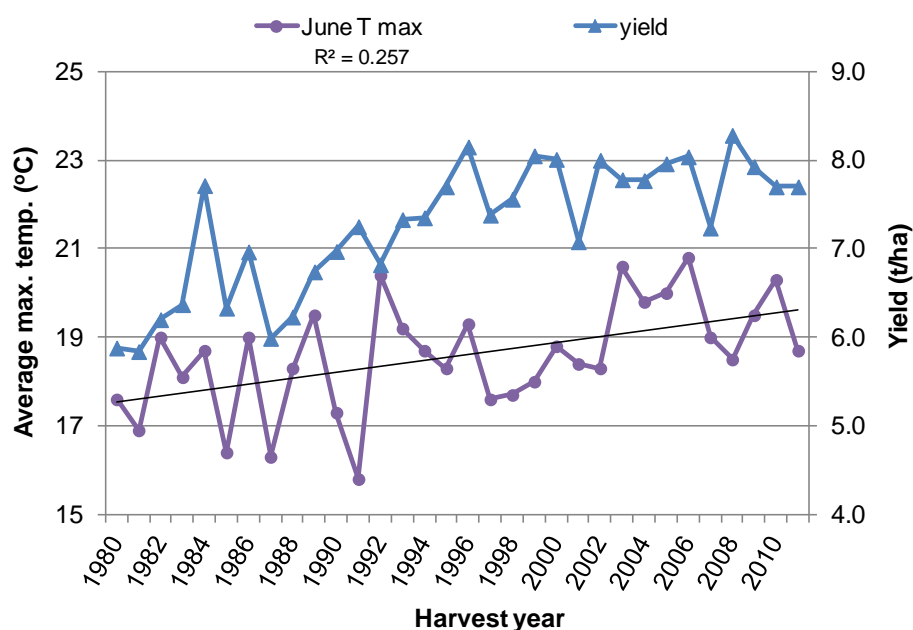


Figure 31. Trends for UK average wheat yield and June maximum temperature for England.

Using mean daily temperatures for June and July for Central England (from the HadCET dataset), the time taken to reach 660 °C days starting from 10 June was calculated for each year. This value was used to represent the average length of the wheat grain fill period. Over the period from 1980 to 2011, a decreasing trend from about 45 to 42 days is apparent (Figure 32). The total number of sunshine hours during grain fill is estimated to have increased from about 250 in 1980 up to 270 by the late 1990s, but plateaued thereafter.

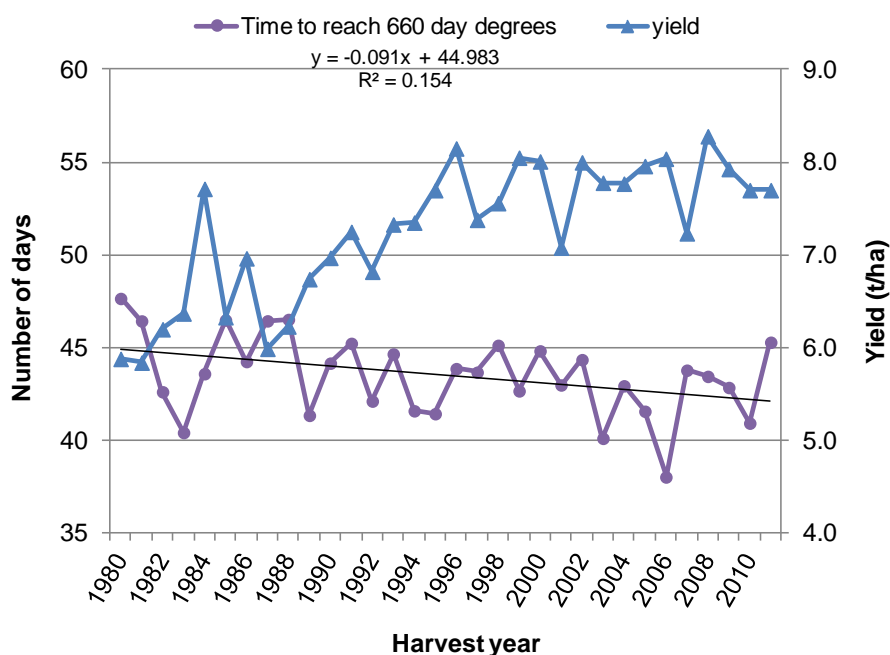


Figure 32. Trends for UK average wheat yield and number of days to reach 660 day°C.

Looking specifically at the possibility of yield depression associated with maximum temperatures in excess of 25°C during or after anthesis, examination of June temperatures for central England and for Cambridge reveals little evidence of a consistent rising occurrence of such conditions (Figures 33 and 34). A weak trend line suggests an increase of about two June days in excess of 25°C over the last 30 years for Cambridge, but segmenting the month into three 10-day sets (Figure 35) reveals that this is largely due to an increase during the final 10-day segment, by which time anthesis would normally be complete for winter wheat. This is different to the situation in France (Brisson *et al.*, 2010) but reflects perhaps the contrast between the cooler, maritime nature of the UK and the warmer continental climate of mainland Europe.

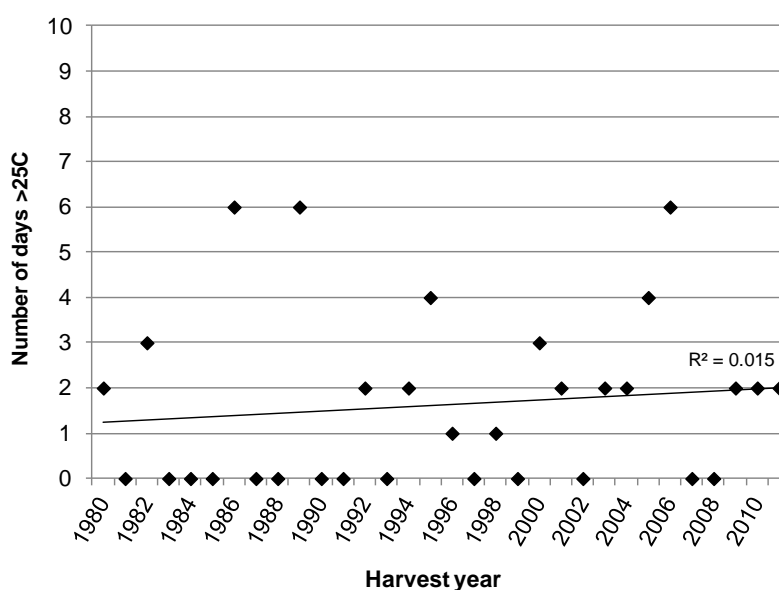


Figure 33. Total June days with maximum temperature above 25°C for central England for 1980-2011.

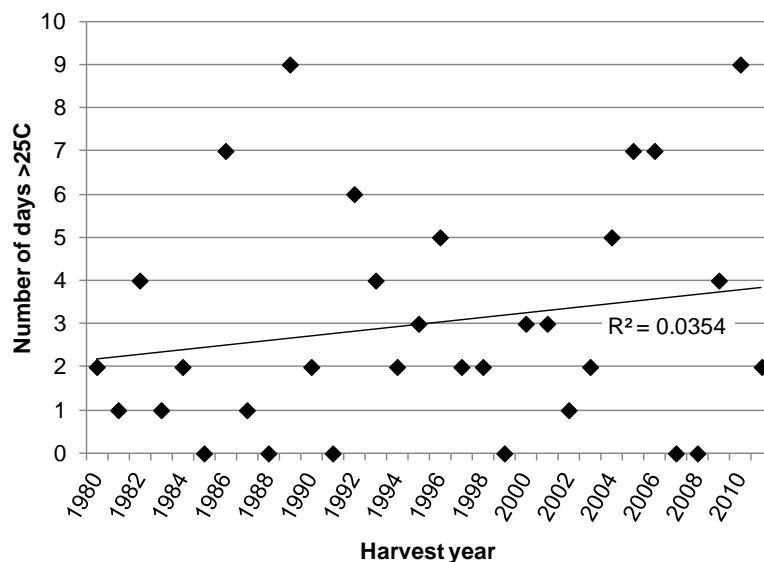


Figure 34. Total June days with maximum temperature above 25°C for Cambridge for 1980-2011.

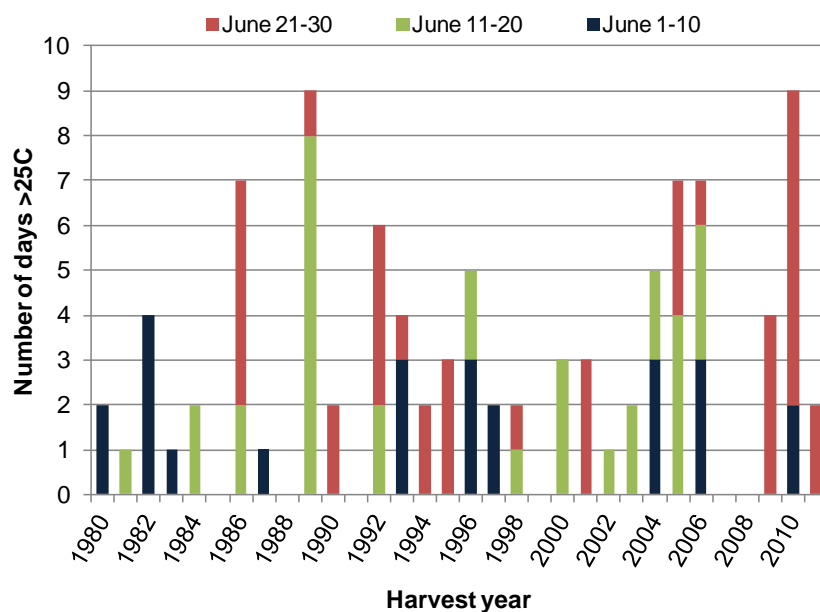


Figure 35. Incidence of days in first, middle and last ten days of June with maximum temperature above 25°C for Cambridge from 1980 to 2011.

Multivariate analysis of weather data

While there may be statistically significant individual correlations of weather data with yield, it is more likely that a combination of several weather patterns simultaneously affect how the crops grow. To study this, weather data were standardised by dividing by two times the standard deviation; this is simply to put these independent variables on the same scale and stop large values of any one variable incorrectly influencing the results. Using a general linear regression, winter wheat was analysed to find weather patterns of interest. Up to sixteen of the variables of greatest individual influence were combined in single analyses to determine the combination of characters that accounted for the greatest percentage variance (sixteen is the maximum that can

be modelled simultaneously with this dataset.) Results were scrutinised to balance the number of variables included and the percentage variance accounted for. Stepwise regression was subsequently also used to assess these data. Initial analysis suggested a combination of weather patterns identified in the single variate correlations play an important role in the resulting yield. Results of this analysis are shown in Appendix Table 7.

However, this result suggests that there is over-fitting of the model to the data; while the model appeared to be reasonable in estimating the percentage variance it could account for, it appeared poor in its ability to predict the influence of weather patterns on future crop growth; ultimately, this is what we want a regression model to do. In order to investigate this potential problem more carefully, the data were analysed by using both Ridge and Lasso regressions (Goeman, 2010).

Using all variables, including year, there are accurate predictions using ridge regression, seemingly without much over-fitting. However, if the year variable is removed from the analysis, then predictions using both ridge regression and lasso are poor. The predictions are all based on year and it appears there are not any obvious weather drivers for winter wheat based on these datasets. The analysis was repeated using subsets of reduced number of variables with closely correlated variables being omitted and by splitting the years into the two 'periods' of wheat indicated before (1980-1996 and 1996-2011). The idea being that, with a reduced set, the regressions might be more interpretable. The analysis was also repeated using residuals from a linear regression on year; again to try and make the data look cleaner and easier to understand.

The data were also analysed using Principal Component Analysis (PCA) to try to visualise how the variables interact with each other and their effect on yield. The PCA shows which variables are 'redundant' and attempts to reduce some of the noise in the data set. However, once year was taken out of the PCA analyses, no obvious patterns in the weather data could be identified.

Other atmospheric changes

Data collected by the National Oceanic and Atmospheric Administration (NOAA) in the US, available at <http://www.co2now.org>, indicate that the mean annual atmospheric CO₂ concentration has increased by about 15% from about 340 to 390 ppmv between 1980 and 2011. Results from a range of whole-season studies reported by Olesen and Bindi (2002) indicate that this could equate to a yield increase of up to about 6% or 0.36 t/ha between 1980 and 2011, equivalent to a potential contribution to yield improvement of about 0.011 t/ha per year.

Wheat is one of the most ozone (O₃) sensitive crops, although this can vary between varieties (Biswas *et al.*, 2008). High ozone concentrations typically occur in summer when the solar intensity is greater, although they fluctuate from year to year due to variability in the weather. Peak ozone

concentrations have decreased over the last 20 to 30 years, because of reductions in emissions of precursor species in Europe (Defra, 2008). Trends in annual mean ozone concentrations in urban areas have increased in recent years due to a decrease in emissions of nitrous oxide (which reacts with ozone). Trends in rural areas are more variable and show less of an increase. Nevertheless, Jaggard *et al.* (2010) concluded that by 2050 rising surface ozone levels are likely to have offset most of the yield increase resulting from increased atmospheric CO₂ levels in C₃ plants like wheat.

Losses of stratospheric ozone over the UK were about 6 per cent between 1980 and the mid-1990s (DOE, 1996a). Although there is no data on the long-term trend in UV-B levels over the UK, in the absence of other changes, loss of stratospheric ozone would be expected to have led to enhanced UV-B radiation. It has been calculated that a 5% decrease in ozone would result in an increase of about 8% in surface UV-B levels. (DOE, 1996b). Hakala *et al.* (2002) observed an impact of UV-B on number of lateral shoots in cereals, but no yield effect. Li *et al.* (1998) observed a decrease in plant height, number of fertile tillers and yield of spring wheat grown at increased UV-B levels. It is possible that increased UV-B levels could have caused a small reduction in wheat yield between 1980 and 2011, which may have negated part of the yield increase that is likely to have resulted from increased CO₂ levels. However, this cannot be quantified with available data.

3.4.6. Economics and policies

Policy and economic factors that may have had an influence on national wheat yield trends are outlined below.

Government policies

From the 1990s UK agricultural policy shifted from a purely productionist approach to an increasing emphasis on supply constraints. The main policy for the arable sector from the 1993 MacSharry reforms was a) lowering of intervention prices, b) compensation for this reduction through the award of area aid according to crop type and c) the management of supply through the introduction of compulsory set-aside of land. A comprehensive review of set-aside indicated that, whilst these reforms had an impact on reducing production area, it had little effect on yield growth throughout Europe (Boatman *et al.*, 1999). Indeed, there is an argument that the reduction of unproductive land at the farm level led to higher average yields per hectare as a result of set-aside.

The Agenda 2000 review of CAP reform emphasised further movement away from production-related goals and this was realised in the 2003 Fischler reform with proposed decoupling of payments. From this period onwards the removal of a direct production support has generated an incentive to decrease production of cereals and oilseeds (Severini and Valle, 2011). The impact of this decoupling on technical change has tended to be negative in the UK, as the incentive for innovation has dampened (Barnes *et al.*, 2011).

Other related policies

A clear impact on yields will be on the underlying research and development funding and practices. The 1980s saw a shift away from applied research, deemed as near-market, toward funding basic research and a number of institutions have been merged or removed from the public sector within the agricultural realm. Further to this, the charging for agronomic advice in England and Wales from 1987 onward, is deemed to have had the effect of reducing technical innovation in both the cropping and livestock sectors (Thirtle *et al.*, 2004; Barnes *et al.*, 2011).

Market prices

Figure 36 shows yield data for wheat compared with prices for both bread/milling wheat and feed wheat as an indication of whether or not there is any influence of prices on yield change. Clearly, the prices and yields follow different trend-shapes but there may be some lag effect in which price signals are leading to changes in yield.

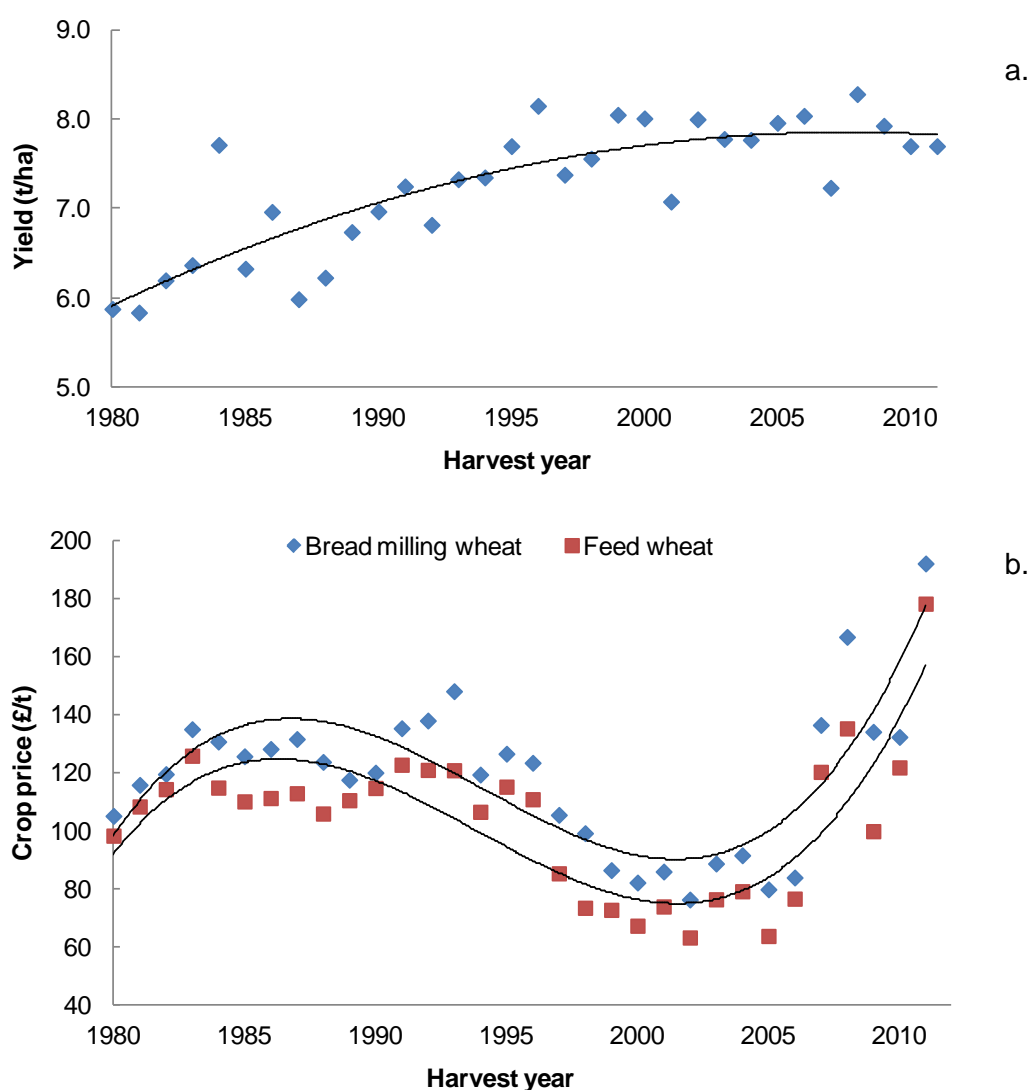


Figure 36. National yield data (a) against market prices (b) for wheat.

In order to explore the relationships between the factors outlined above a regression analysis was run on causal factors (wheat prices and policies) against yield change over the 1988-2011 time period. A number of regressions were run, but weather variables had to be removed as they led to biased estimators. As there was no evidence of previous year's yield affecting this year's yield, an Ordinary Least Squares (OLS) regression with lagged prices ($t-1$) was used to explain the effect on yield. Ultimately, the price data proved difficult to fit within the regression using a series of lag lengths and shapes. Table 7 shows the results of the best run, with an R^2 of 0.64.

Table 7. Results of regression on wheat yields (BM: Bread/milling Wheat; F: Feed Wheat)

Wheat Yields	Coef.
Intercept	-0.016
Price(BM _{t-1})	-0.075
Price (F _{t-1})	0.095
d93 MacSharry	0.048**
d05 decoupling	0.004

The results indicate that, over the period as a whole, grain prices, even lagged by one year, have had no significant effect on yields achieved. It can be speculated that changing prices might have an influence in the medium term. However, applying a series of lag lengths up to 5 years found no significant effect. Changes to the lag shape (to reflect a slower diffusion of price effects on yield) could not be fitted satisfactorily either. A weakness in this approach is the use of a mean price against a mean yield. Therefore regional variation has been removed from the analysis. If consistent data were available, a regional analysis might pick up more of a price effect on yield. Increased price volatility since 2005 may be holding back the adoption of new technologies or increased management intensity, even though average prices have increased. There is evidence of policies having had an impact on wheat yield. The decoupling reforms appear to have had no significant effect, but the MacSharry reform dummy appears to have had a positive impact. This reflects the findings of Boatman *et al.* (1999) indicating that set-aside had the effect of removing unproductive land from production and bolstered yields.

Data from the Farm Business Survey show that between 2004 and 2009 wheat gross margins were highest for farms in the top yield quartile and lowest for farms in the bottom yield quartile. Differences were smallest in 2005 when wheat grain prices were at their lowest (Figure 37).

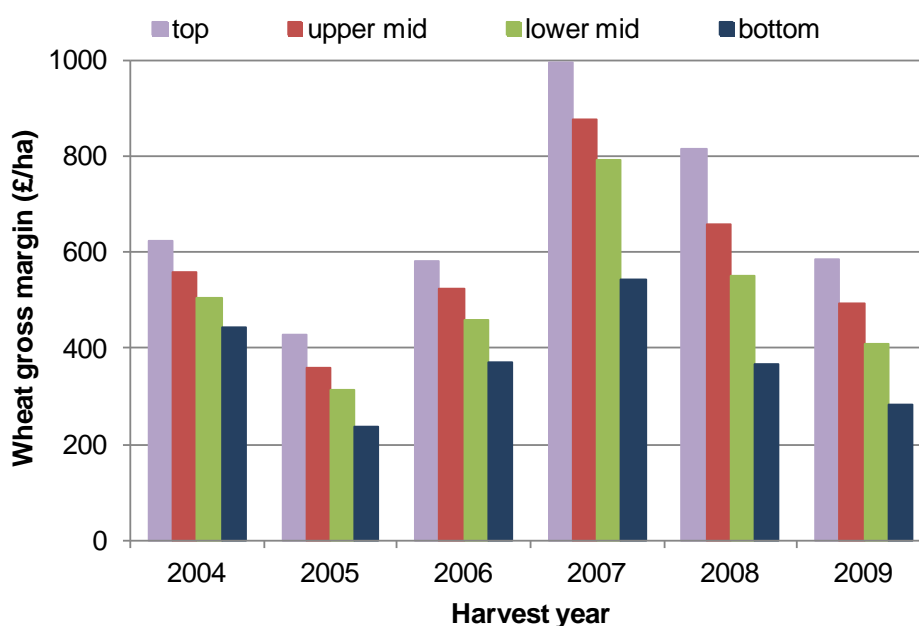


Figure 37. Mean wheat gross margins achieved by FBS top, upper middle, lower middle and bottom yield quartiles.

Over the 2004-2009 period, labour, contract and machinery (rental, depreciation, repairs and fuel & oils) costs per hectare have generally been higher for farms in the top wheat yield quartile than for farms in the bottom yield quartile (Figure 38). In addition, since 2005, costs have increased more rapidly for those in the top yield quartile than those in the bottom yield quartile, with the difference increasing from £50/ha or less in 2004 and 2005 to £100/ha in 2008 and 2009. This could mean that farms in the top yield quartile are investing more in the production of the crop, and achieving better timeliness and field efficiency, although they may also have other enterprises that are influencing the requirement for labour and machinery.

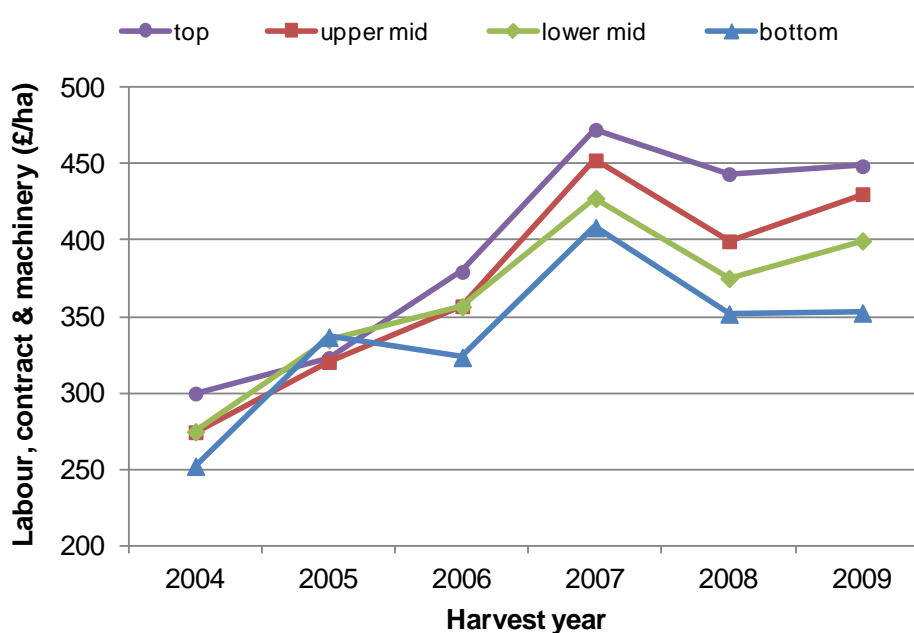


Figure 38. Labour, contract and machinery spend by FBS top, upper middle, lower middle and bottom wheat yield quartiles.

Deducting labour, contract and machinery costs from gross margins for each quartile, it is evident that farms in the top quartile for yield consistently have a positive margin, whereas those in the bottom quartile don't (Figure 39). However, the differences in margin between top and bottom yield quartiles are reduced by the differences between their labour and machinery costs (Figure 38).

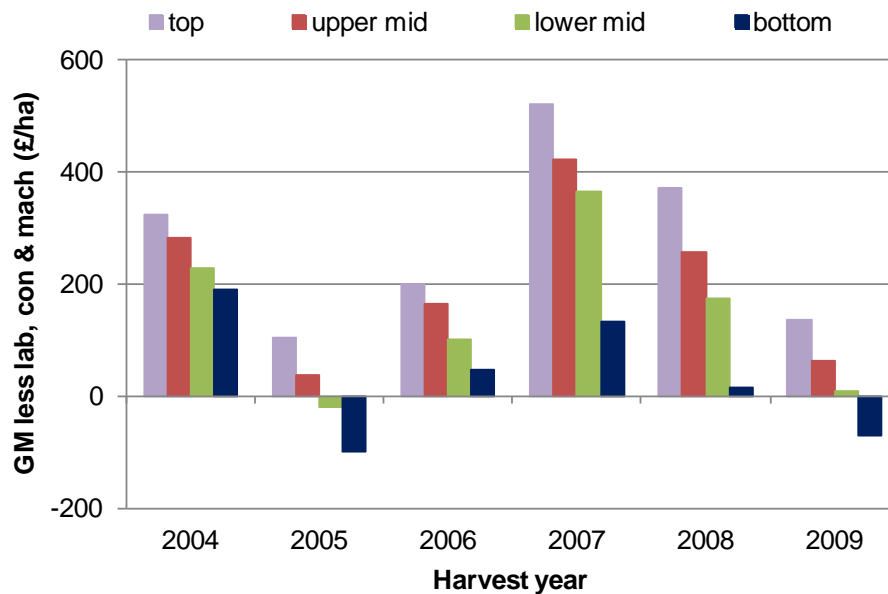


Figure 39. Gross margin less labour, contract and machinery costs for FBS top, upper middle, lower middle and bottom wheat yield quartiles.

3.4.7. Factors influencing recent yield trends in RL trials

Recent trends in HGCA RL trials can be investigated further by looking at yields within climatic regions and agronomic factors. This short-term (2002 - 2011) yield analysis represents net effects of genetic and seasonal influences, with the latter subject to highly variable weather patterns from year to year. However, it is possible to examine several important influences on yield trends within the RL data base for comparison with UK farm yields although it should be noted that this analysis was not able to separate variety and year variables.

The overall treated yield trend for varieties in their first year on the RL (year 1 varieties) was an increase of 0.04 t/ha per year (Figure 40, Table 8). The difference between the mean yield for year 1 RL varieties and the UK farm average over this period increased at a rate of 0.054 t/ha per year (Table 9). This indicates that new entries to the RL, over this short time period, continued to increase their performance advantage over the UK average.

Different yield trends were apparent across RL climatic regions, with the wetter West and cooler North (Figure 41) increasing at 0.025 t/ha and 0.082 t/ha per year, respectively. This contrasts with an improvement of less than 0.01 t/ha for the same varieties in the dry East. Extending this

analysis to soil type, fungicide-treated yield improvement on heavier textured soils was 0.067 t/ha per year (Figure 42). In contrast there was no correlation for yield results on lighter soils, which experienced relatively low yields in harvest years 2005 to 2008. Although subject to high seasonal variation, the differential between heavier- and lighter-textured soils over the last ten years increased at 0.065 t/ha per year. Both of these support suggestion of a significant climatic / weather impact on the performance of wheat in at least some areas within the East region.

There was a consistent yield improvement for early sown RL crops of 0.071 t/ha per year (Figure 43). Yield improvement in first wheat crops was relatively small at 0.017 t/ha per year, as was the differential between first versus second (or more) year wheats; this was largely because of relatively good yields in second (or more) year wheat between 2006 and 2009.

Differences between RL treated yield and the UK farm average (*i.e.* 0.054 t/ha per year) can also be examined for agronomic features (Table 9). For example the gap between RL year 1 varieties on heavier textured soils and the UK farm average was increasing at 0.081 t/ha per year, whilst the differences between RL early sowing and RL first wheat and the UK farm average were increasing at 0.077 t/ha and 0.031 t/ha per year, respectively.

Table 8. Yield trends in HGCA RL trials over harvests 2002 to 2011. The annual yield change is based the slope of a linear regression of yield across years for varieties in their first year on the RL. The proportion of variation explained by fitting the line is R^2 . The standard error of the regression coefficient and significance of the regression (F -distribution) are presented.

RL data set	Annual yield change (t/ha)	R^2 of fitted line	se of regression coefficient	Significance F
Fungicide treated	0.040	0.382	0.0179	0.057
Dry East region	0.005	0.012	0.0174	0.764
Wet West region	0.025	0.124	0.0233	0.319
Cool North region	0.082	0.586	0.0243	0.010
Heavy textured soils	0.067	0.320	0.0347	0.088
Light textured soils	0.003	<0.001	0.0377	0.945
Early sowing	0.071	0.604	0.0217	0.014
First wheat	0.017	0.072	0.0210	0.452

Table 9. Difference between RL trials and UK farm average over harvests 2002 to 2011. The annual yield change for RL trials is based the slope of a linear regression of yield across years for varieties in their first year on the RL. The proportion of variation explained by fitting the line is R^2 . The standard error of the regression coefficient and significance of the regression (F -distribution) are presented.

Comparison of RL trial and UK farm average	Annual yield change (t/ha)	R^2 of fitted line	se of regression coefficient	Significance F
RL treated – UK farm average	0.054	0.226	0.0351	0.165
RL heavy textured soils – UK farm average	0.081	0.224	0.0535	0.167
RL early sowing – UK farm average	0.077	0.302	0.0441	0.125
RL first wheat – UK farm average	0.031	0.068	0.0402	0.469

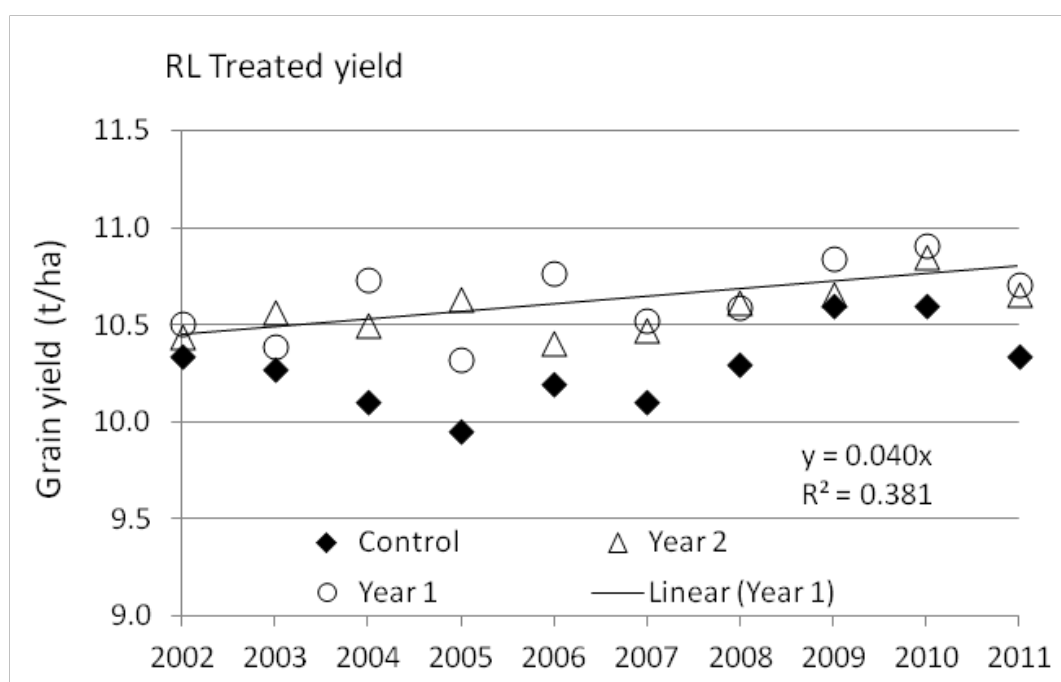


Figure 40. Treated yield trend for varieties in their first years on the RL.

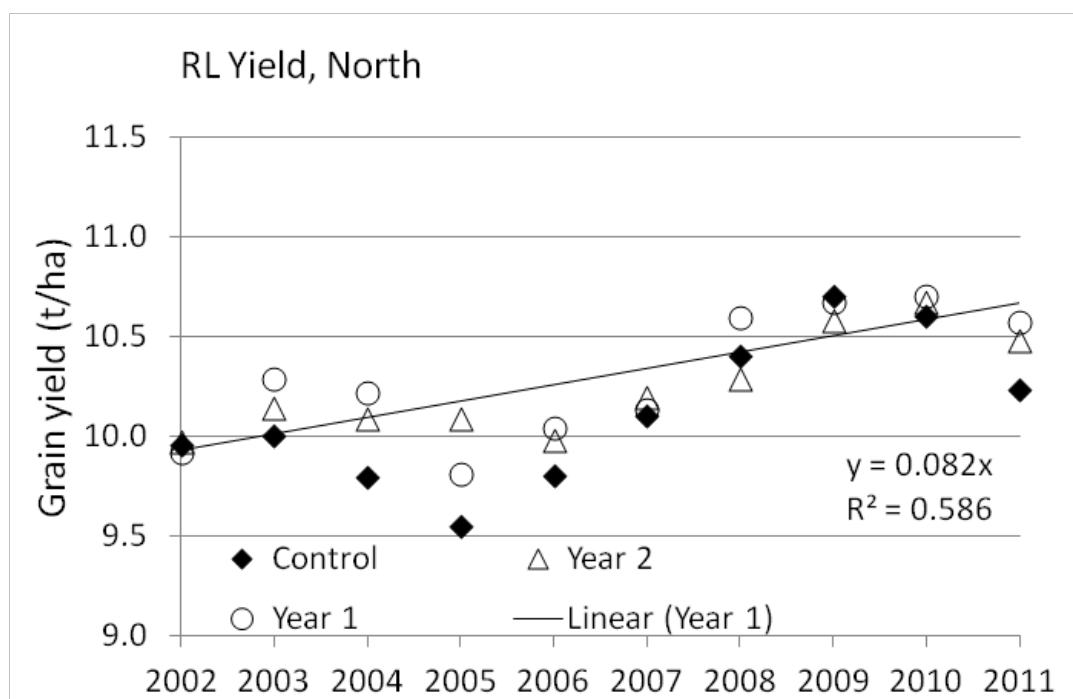


Figure 41. Cooler, north region yields, for varieties in their first years on the RL.

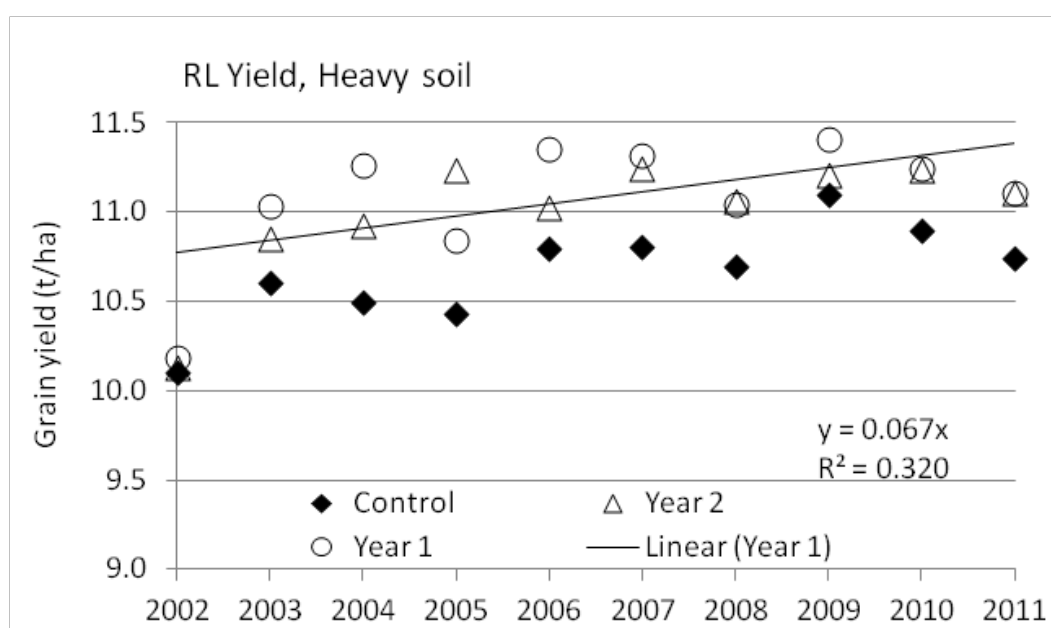


Figure 42. Heavy land yield trend for varieties in their first years on the RL.

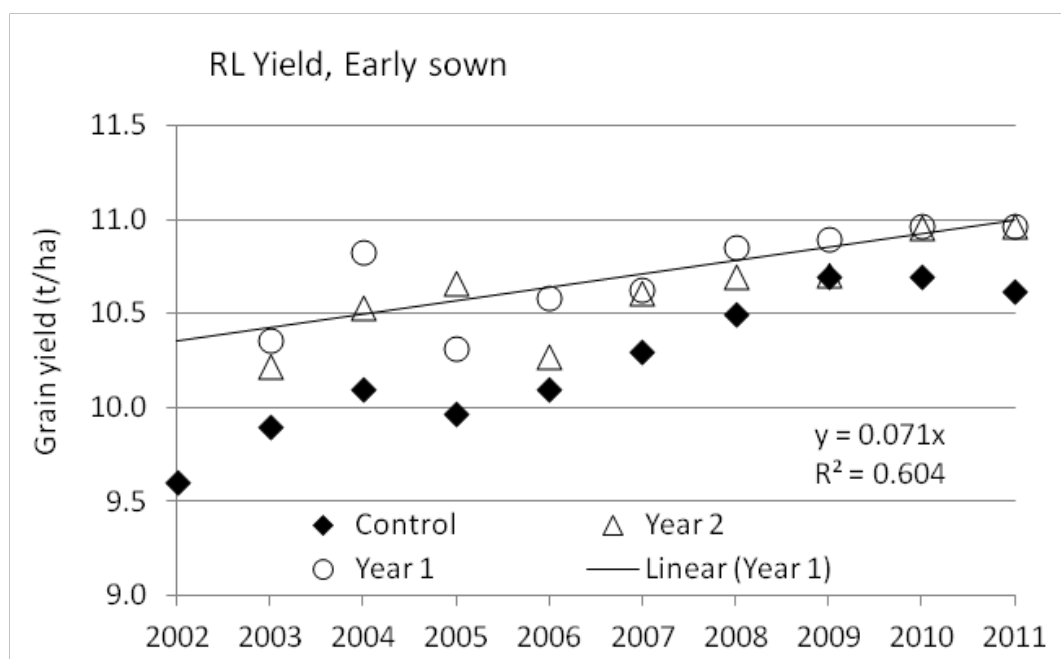


Figure 43. Early sown yield trend for varieties in their first years on the RL.

3.4.8. Crop nutrition and fertiliser use

Nitrogen

Fertiliser use statistics from the British Survey of Fertiliser Practice indicate that overall rates of N application to winter wheat crops have remained relatively constant from the early 1980s onwards at around 180-195 kg N/ha (Figure 44). As the vast majority of crops received some application of fertiliser N (98-99% of crops, data from 1998 onwards), the overall rate applied reflects the average field rate of application. The static rates of N application cover the period of increasing yields from 1980 to the mid-1990s and the yield plateau that follows. Prior to the latest revision of the fertiliser manual RB209 (8th edition) N recommendations were based on over 280 N response experiments conducted largely between 1981 and 1994 using varieties with a significantly lower yield potential than modern varieties (Sylvester-Bradley *et al.*, 2008). There has been concern within the industry that under-use of N fertiliser may have contributed to the lack of yield improvement on farm over the last decade whilst the genetic yield potential continued to increase.

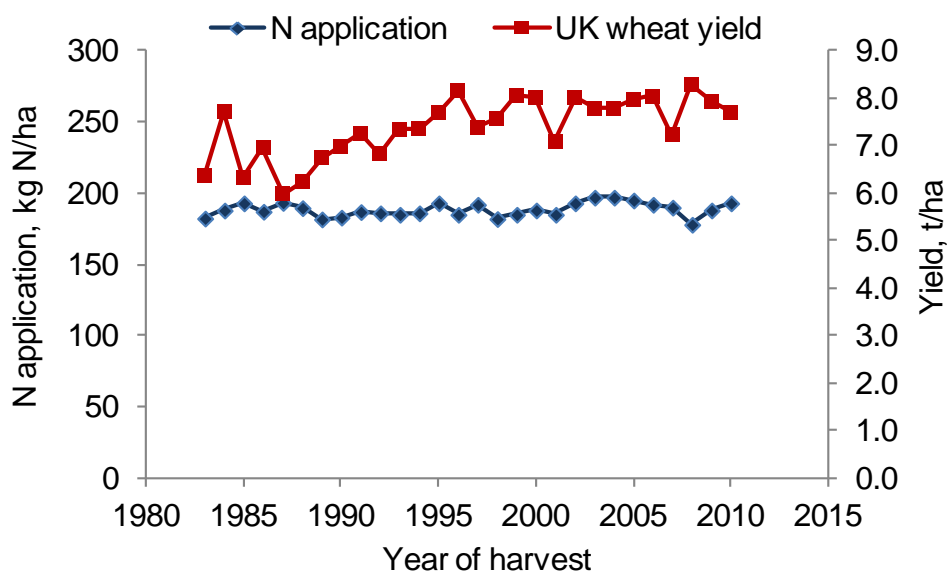


Figure 44. Average field rates of N fertiliser application to wheat crops and national average yields.

A recent HGCA-funded study (Sylvester-Bradley *et al.*, 2008) that compared the N responses of old (introduced in the 1980s) with modern (introduced in the 2000s) varieties found that the economic optimum rate of N (Nopt) at a break even ratio (BER) of 3:1 (price per kg of N / price per kg of grain) was greater in modern varieties by about 20 kg N per tonne of yield improvement. Although the increase was slightly less than might have been predicted from the improvement in yield at Nopt, indicating that breeders could have inadvertently increased N use efficiency when selecting for yield (Foulkes *et al.*, 1998; Sylvester-Bradley *et al.*, 2008), Sylvester-Bradley and Kindred (2009) subsequently concluded that there had in fact been little or no improvement in efficiency. This would suggest that the use of the same N fertiliser recommendations for modern varieties with higher yield potential may have constrained improvement in on-farm yields. Using the differences in Nopt for old and modern varieties and the 'standard' N response curve for wheat reported by Sylvester-Bradley *et al.* (2008), it is estimated that using fertiliser recommendations based on Nopt of old varieties would on average limit yield of modern varieties by up to 0.12 t/ha.

Nopt is the fertiliser rate at which the expense incurred from further addition of fertiliser will not be covered by returns from the additional grain produced. It thus depends on the purchase price of the fertiliser and sale price of the grain in addition to the crop N demand and N use efficiency. The BER for N fertiliser was relatively stable during the 1980s and early 1990s but began to rise with falling grain prices towards the end of the 1990s. From 2000 onwards the ratio rose sharply, driven by rising fertiliser costs and low grain prices, and has fluctuated widely since then, reaching a peak of 7 around 2005. An increase in BER reduces the Nopt, placing a further constraint on yield. The 8th edition of RB209 published in 2010 accounts for both the increases in crop N requirement of modern varieties and the higher BER in its recommendations for fertiliser N.

Orson (2010) reviewed 54 winter wheat N response experiments conducted by NIAB TAG between 1997 and 2009, on long-term arable soils. These were all located on deep clay, medium or shallow (over chalk or limestone) soils, with no recent organic manure and with soil organic matter of 4% or less. Previous crops included cereals and break crops including sugar beet. The average N_{opt} for a BER of 3:1 was 241 kg N/ha, and was unaffected by previous crop or soil mineral N (SMN) level. Based on the Field Assessment Method and N recommendations for a BER of 3:1 set out in the 7th edition of RB209, which was the version in use for much of that period, the average SNS index for the 54 experiments would have been 2 (range 1-4), and the average N recommendation about 190 kg N/ha (range 100-240). This implies that advice at the time may have led to under application of N fertiliser in situations representing a significant proportion of wheat crop area. It is known that by no means all growers followed the N recommendations set out in RB209, relying instead on their own experience or on recommendations provided by their agronomist. However, the national average rate of fertiliser N applied to crops between 1997 and 2009 was also about 190 kg N/ha.

Figure 45 shows the trend over time in grain N % (at 100% dry matter), derived from grain protein records for Great Britain from the HGCA Cereal Quality Survey (and adjusted for the moisture content at which the protein contents would have been recorded). The decline in grain N contents mirrors the increase in UK grain yields, falling from 1980 through to the mid-1990s but then starting to level off. This could indicate that the supply of N was becoming more limiting as yields increased between 1980 and the mid-1990s. However, it should be noted that, as illustrated in Figure 18, there were also some changes in the proportions of varieties from each nabim group that were being grown over this period, which may have confounded this analysis.

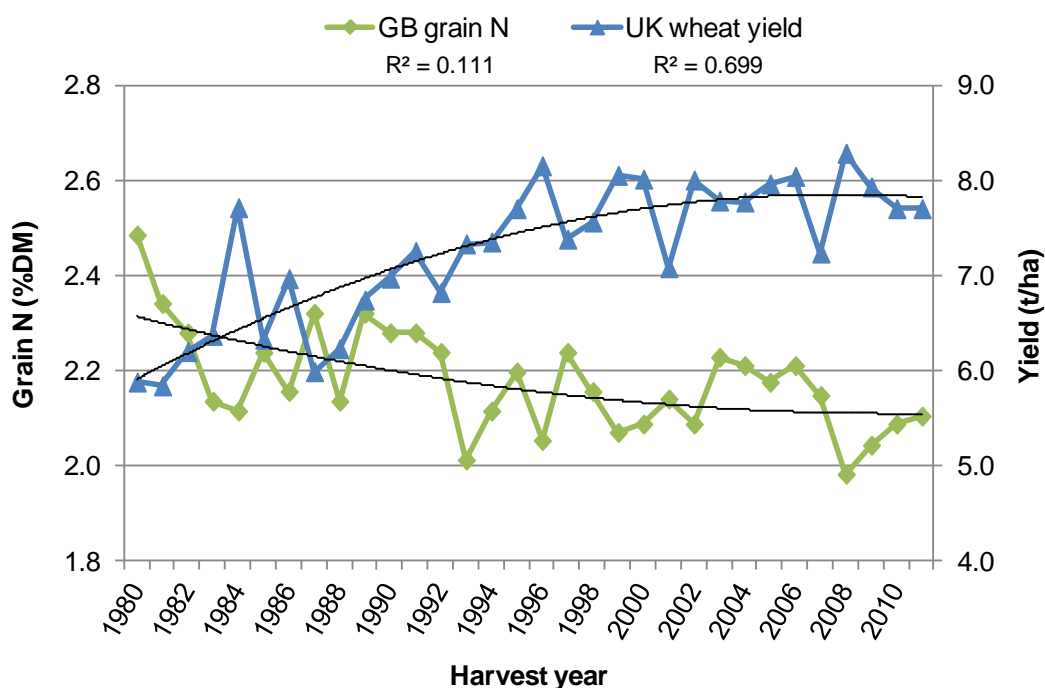


Figure 45. Average wheat grain N content (%DM) for Great Britain from 1980 to 2011.

Phosphate and potassium

Maximum yields of cereals are usually achieved with a soil phosphate (P) index of 2 and potassium (K) index of 2- (or its equivalent 'moderate' status in Scotland). Applications of P and K fertiliser to soils with indices at or above these levels rarely give significant yield increase. With fertiliser costs rising, the suitability of index 2 as the target for soil P has been questioned. A review of three long-term experiments involving soil with wide ranging P status examined the relationship between soil P and yield of winter wheat. In 55% of cases maximum yields were obtained with soils at P index 0 and 1, in 30% of cases soils at index 2 and in 15% of cases soils at index 3 (Johnston & Poulton, 2011). This implies that, as a measure of P sufficiency, index 2 is conservative. As P is relatively immobile in soil, good root exploration is required for efficient capture and a higher soil index may be needed to meet crop demand where soil structure is poor (Johnston & Poulton, 2011).

The principle of P and K management is to bring deficient soils up to the target non-limiting index for the rotation and then to maintain it at that level by applying fertiliser or manures to replace P and K removed in the crop. Where the soil index is well above target, guidelines recommend that fertiliser applications be reduced below the crop replacement amounts to allow the soil index to decline to the target level. According to the British Survey of Fertiliser Practice, overall application rates of P and K fertiliser to commercial wheat crops have steadily declined since 1996 from rates of around 55 kg/ha of P_2O_5 and K_2O in 1996 to approximately 20 kg/ha or less in 2009 (Figure 46). Although the timing of the decline coincides with the onset of the yield plateau for wheat, there is little evidence to suggest that P or K deficiency have contributed to the lack of yield improvement.

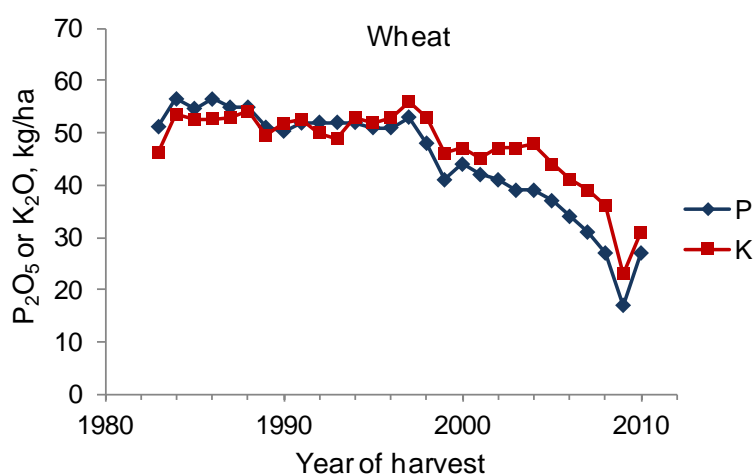


Figure 46. Overall application rates of P and K fertiliser applied to crops of wheat.

The reduction in overall rate of P_2O_5 applied from 1996 onwards was associated with a small (20%) decline in average rate of application per treated crop, but a large reduction in the percentage of wheat crops that were treated (Figure 47a). By contrast, there has been little change

in the average rate of K_2O application over the same time period, implying that the reduction in overall rate (Figure 47b) was largely the result of fewer crops being given K fertiliser.

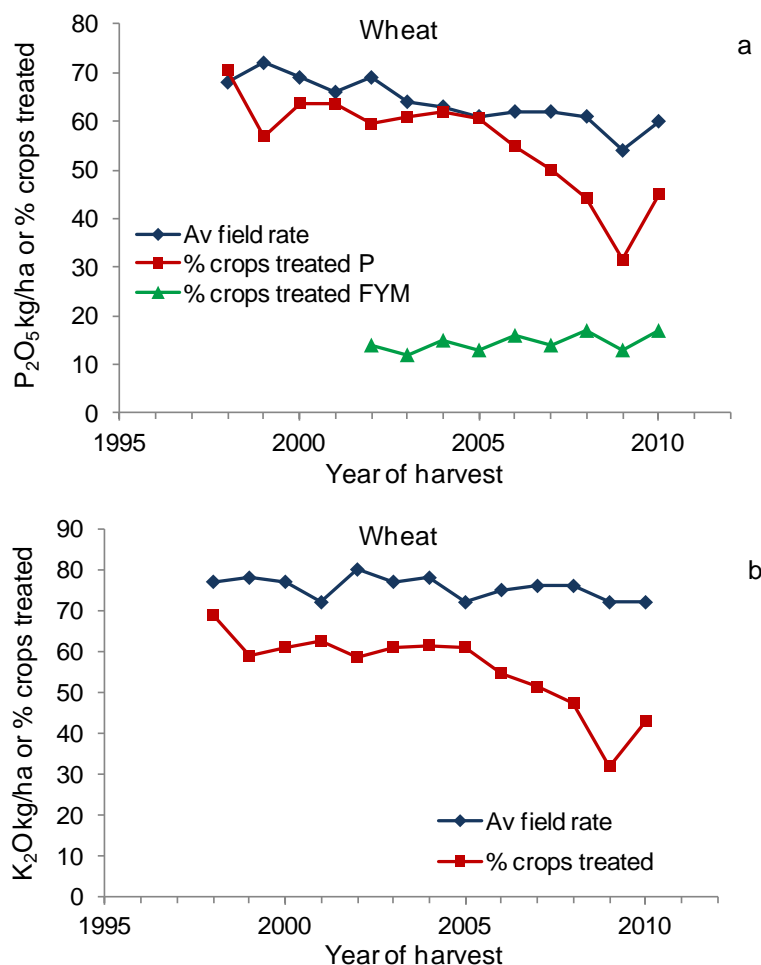


Figure 47. Average application rates per treated wheat crop and % of crops treated with (a) P_2O_5 and (b) K_2O fertiliser.

The net P_2O_5 and K_2O budgets for the national wheat crop can be estimated as the difference between the amount applied in fertiliser and that removed in grain or grain and straw. The latter is estimated from the national average grain yield in a given year, the % of crops from which straw was removed and typical off takes in grain and straw per tonne of grain yield (Defra, 2010a). Figure 48 shows that there has been a net deficit in the P_2O_5 and K_2O budgets for wheat crops from the early 1990s onwards. However, this is a rather simplistic analysis and does not account for whether the shortfall for the wheat crop was made up with additional applications elsewhere in the rotation. There has been little change in the % of crops receiving manures which suggests that the decline in overall application of inorganic P and K was not because fertilisers were being increasingly supplemented with organic sources of these elements.

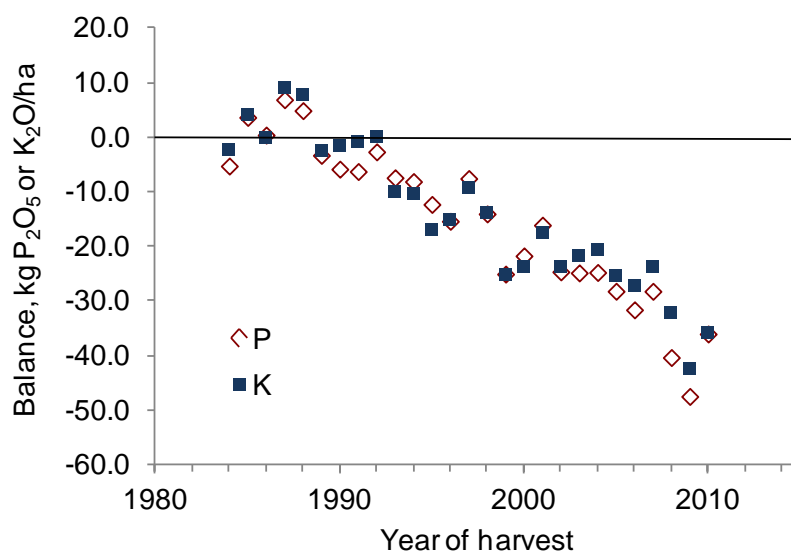


Figure 48. Net budget of P₂O₅ and K₂O applied in fertiliser to wheat crops and that removed in harvested grain or grain plus straw.

Changes in the P and K status of soils over time are illustrated in Figure 49. The data are compiled from soil samples sent to NRM Ltd for analysis and are based on an average of about 23,000 samples from arable fields per year. The results have been summarised into three categories; those where the index is less than the target of 2, those that are at the target and those above the target. For P, the majority (>40%) of soils tested were above target, a little over 30% were at the target and the minority (around 20%) were below target. More importantly, there was no major change in the soil index categories over time. Thus in spite of the rising net P₂O₅ budget deficit for wheat crops, the percentage of soils at or above the target index has remained relatively stable. If anything, the percentage of soils above target appeared to increase between 2008 and 2010. Between 1996 and 2003 the K status of most soils was below target. However, since then the K status appears to have increased so that the percentage in each category was roughly the same in 2009 and 2010. As with P, this is in spite of the growing net deficit in K₂O budget for wheat crops.

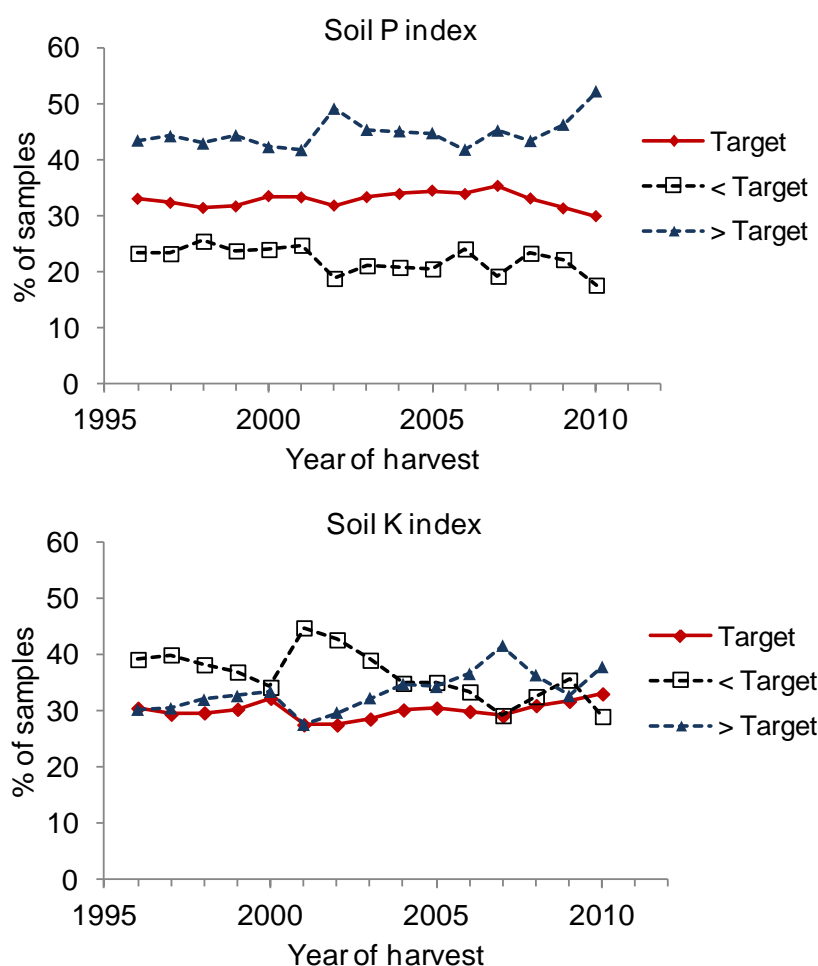


Figure 49. % of soil samples from arable fields received for analysis that were below (< Target), at (Target) or above (> Target) the soil index of 2 for P_2O_5 and K_2O (source: NRM UK).

Figure 50 compares the percentage of wheat crops not given a dressing of P or K fertiliser with the percentage of arable soil samples sent for analysis with an index above 2. Given that these data are taken from different sources, prior to 2007 the two sets of values are in remarkably close agreement. For P the percentage of crops left unfertilized was marginally less than the percentage of soils above target, and for K the percentage of crops was marginally greater. After 2007, the percentage of crops not treated increased.

The national trends in fertiliser application and soil P and K status highlighted above are consistent with a nutrient management policy of running down the P and K status of soils that are above the target index. The observation that the percentage of soils above the target index has not declined in spite of growing net budget deficits for wheat, the most widely grown arable crop, is surprising and perhaps a reflection of the buffering capacity for P and K in many soils. A further examination of soil sampling and analysis trends may also be justified. Nevertheless, there is no evidence from these data that insufficient P or K have been a constraint to wheat yield from 1996 to date.

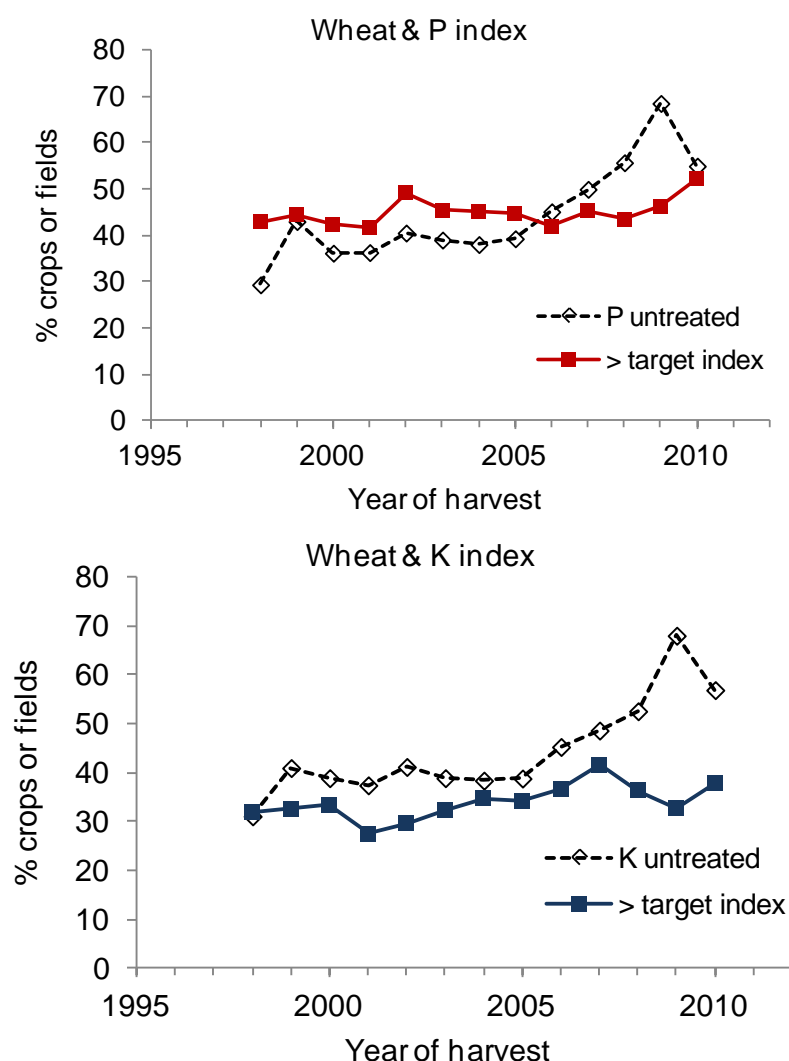


Figure 50. Percentage of wheat crops not treated with P or K fertiliser compared with the percentage of soil samples from arable fields above the target index of 2.

Sulphur

Historically inputs of sulphur (S) from atmospheric deposition and as co-products of N/P fertilisers like ammonium sulphate and single superphosphate were more than enough to meet the needs of UK crops. However, the large decline in levels of atmospheric deposition and reduced popularity of S-containing fertilisers during the 1980s led to increasing problems of S deficiency in oilseed rape and wheat. Availability of S in soil solution for crop uptake is governed by the balance of S inputs from fertiliser, atmospheric deposition and mineralisation of organic S, and S losses principally via leaching of sulphate from the soil. Soil texture, organic matter content and climatic factors such as temperature and rainfall have a significant effect on rates of mineralisation and leaching.

McGrath and Zhao (1995) developed a qualitative model to assess the risk of S deficiency in UK cereal crops based on soil type, rainfall and sulphur deposition. They concluded that 11% of the UK land area was at high risk of sulphur deficiency and a further 22% at medium risk. In 2007 the predictions were revised to take account of the significant reduction in S deposition that occurred

between 1990 and 2000-2004, and the distribution of arable land in the UK (Cussans *et al.*, 2007). The revised predictions were of 16% of cereal crops being at significant risk of S deficiency in 1990 and 25% at medium risk, rising to 30% at high risk and a further 30% at medium risk in 2000-2004. The figure of 30% of crops at high risk agreed well with the results of field trials in which 26% of wheat trials showed a significant positive response to S fertiliser (Cussans *et al.*, 2007), although Carver (2005) reported a lower number (11%) over a similar period. Between 1990 and 2000 the UK average rate of S deposition declined at 0.6 kg/ha per year (Cussans *et al.*, 2007). Since 2004, the S deposition rate has continued to decline at the same rate (Defra UK deposition data 2012) suggesting that the risk of S deficiency may have increased further in some areas.

Survey data of fertiliser applications to commercial wheat crops show that before 1995 less than 10% of the area was treated with S; below the 16% predicted to be at high risk of S deficiency in 1990 (Figure 51). Between 1998 and 2000 the treated area had increased to 15% but was still lower than the 30% of crops predicted to be at high risk in 2000-2004. The area treated increased to 30% by 2003 and 40% by 2005, after which it has remained relatively stable. The average rate of application to treated crops rose from 20 kg SO₃/ha in 1993 to its current level of 50 kg SO₃/ha by 2000. The results demonstrate that growers have responded to advice about the need to apply S fertiliser over the last 15 years, but that there may have been a lag in the uptake of that advice.

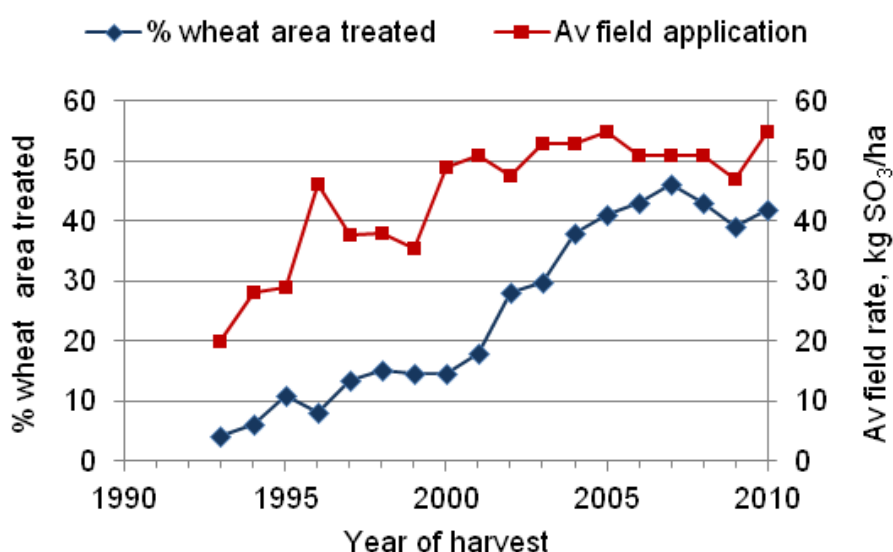


Figure 51. Percentage of wheat area receiving S fertiliser and the average field rate of application.

The precision of these estimates is uncertain due to the nature of the data. The analysis does not account for inputs of S from manures, and it is possible that some crops at risk are receiving these instead of inorganic S fertiliser. Nevertheless the results suggest that S deficiency is likely to have had an influence on farm yield progress. In high risk situations, responses to S fertiliser application can be large. In a meta-analysis of 88 field trials at 21 sites, yield increases averaged 27% (range 2 - 59%) at responsive sites, (Cussans *et al.*, 2007). Assuming that the percentage of crops at high

risk increased linearly from 16 to 30% between 1990 and 2002, it is estimated that S deficiency may have reduced national average yields by up to 0.4 t/ha in the mid-1990s. It is assumed that the yield reduction increased between the 1980s and mid-1990s in line with the area at risk from S deficiency, but it has not been possible to quantify the rate at which this occurred with certainty.

By the early 2000s the estimated reduction in national average yields had decreased to less than 0.2 t/ha, indicating an average contribution to yield improvement of up to 0.025 t/ha per year from 1996 to 2002. This relatively large figure may well be an over-estimate, as not all crops treated are likely to have been those at highest deficiency risk. From 2003 the situation is less clear, but the rise in area treated with S is thought to have been sufficient to keep pace with the increase in area at high risk of deficiency, and it is assumed that there would have been little net impact on the yield trend. However, there is again no certainty that the additional crops being treated were those at highest risk. Even if they were, it still leaves 20-30% of crops potentially at medium deficiency risk that were not being treated. Yield responses in these medium risk situations are difficult to predict, but they are likely to be relatively small and variable (Carver, 2005; Cussans *et al.*, 2007).

Secondary/trace elements and pH

Deficiencies of secondary macronutrients and trace elements (micronutrients) are sometimes identified as a possible barrier to the achievement of higher yields. Key elements of interest in wheat are magnesium (Mg), manganese (Mn), copper (Cu) and zinc (Zn). Since the mid-1960s concentrations of Cu, Zn and Mg in wheat grain have decreased in samples taken from the Broadbalk Wheat Experiment at Rothamsted (Fan *et al.*, 2008), without a reduction in concentrations in the soil. This has been attributed to increasing yield and harvest index.

Mg deficiency is most common on light sandy and thin chalk soils. Lasting symptoms may occur in wheat where the soil Mg Index is low (index 0, <26 mg/litre). Transient symptoms appear more often, where rooting is restricted or in drought conditions. Yield responses to Mg application are rare, and prevention of yield loss relies on maintaining a soil Mg Index of at least 1 (26+ mg/litre) unless more responsive crops are being grown in the same rotation (Defra, 2010a). Data from an average of 23,000 soil samples per year from arable fields sent for analysis to NRM reveal that on average only 3% of samples have been at soil Mg Index 0, with no increase from 1995 to 2010. 75% of samples have been at soil Mg Index 2 or above. Some of the farms will have been growing crops that require a soil Mg Index higher than 1 to be maintained. Although transient symptoms have been reported in recent dry springs there is no evidence to suggest a trend towards increasing Mg deficiency that is likely to have impacted upon national wheat yields.

Mn is the most common trace element deficiency in wheat, particularly on organic soils or sandy soils with high pH. Transient deficiencies may occur where root uptake is poor due to dry 'fluffy'

seedbeds or waterlogging. Diagnosis relies on leaf tissue analysis. Cu deficiency is most common in cereals growing on sand, peat, heathland or shallow chalk soils. Soil analysis is most useful for identifying deficiency risk. A comparison of 132 arable soils sampled in 2009/2010 with agricultural soils from the National Soil Inventory sampled in 1978-1982 (McGrath & Loveland, 1992) indicated that the Mn, Cu and Zn status of soils may have decreased over the last 30 years (McGrath, 2012). Data from 10 field experiments (HGCA project 3508, on-going) in 2010 or 2011 on organic, loamy sand, sandy loam or calcareous soils at risk of deficiency showed no wheat yield increase from the application of Mn, Cu or Zn (McGrath, 2012). Leaf analyses showed lower levels of all elements in 2011 than in 2010, with results for leaf and grain analyses mostly in agreement for Mn and Zn, but not always for Cu. Low leaf or grain concentrations occurred without obvious yield effects. There is little evidence therefore to implicate trace element deficiencies as a cause of yield stagnation.

Soil samples analysed by NRM also show that about 40% of arable fields are within the optimum pH range for wheat of between 6 and 7, with no change between 1995 and 2010. Between 1995 and 2007 the proportion of samples with a pH below 6 doubled from 10 to 20%, with a 10% fall in the proportion of samples above pH 7, but from 2007 to 2010 this shift was reversed. The possible increase in fields below pH 6 may have had a minor effect on wheat yields from 1995 to 2007.

Differences between farms

Farm Business Survey data show that farms in the top wheat yield quartile are spending slightly more per hectare on fertiliser than farms in the bottom yield quartile (Figure 52), although the gap between the top and bottom quartiles has varied over the period analysed. However, farms in the top quartile for wheat gross margin are spending less on fertiliser than farms in the bottom quartile, although there was little difference in 2004 and 2007 (Figure 53). This doesn't necessarily mean that farms in the top gross margin quartile have been using less fertiliser (they may have been buying it more competitively) or that farms in the top gross margin quartile have limited their yields (they may have had a lower fertiliser requirement).

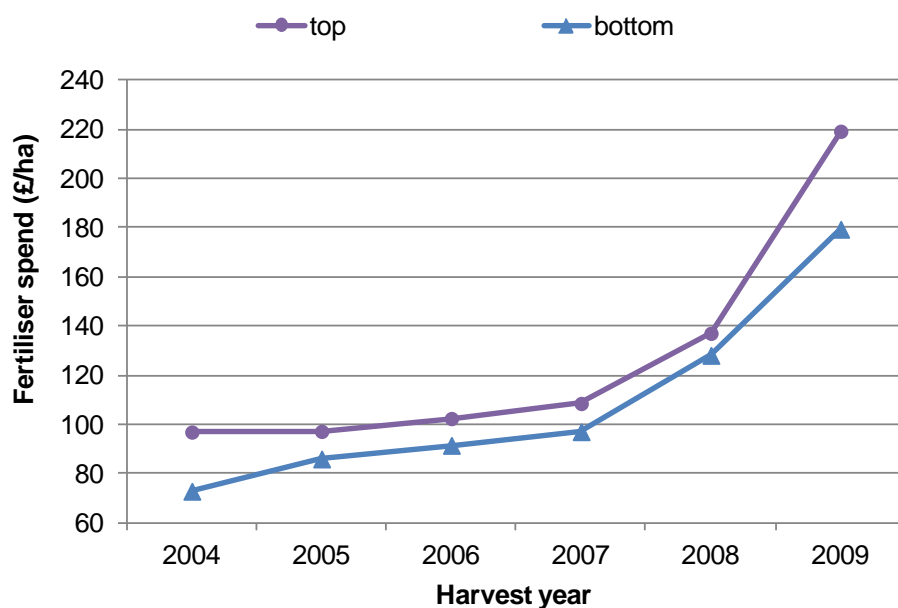


Figure 52. Fertiliser expenditure for FBS top and bottom quartiles for wheat yield.

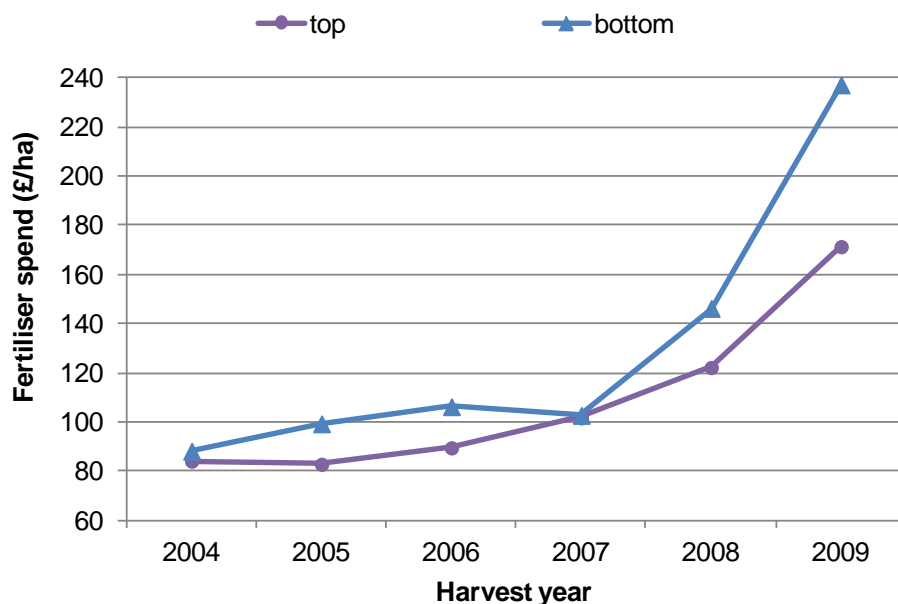


Figure 53. Fertiliser expenditure for FBS top and bottom quartiles for wheat gross margin.

3.4.9. Crop protection and pesticide use

Varying amounts of information were available for analysing changes in crop protection over the last 30 years. Annual wheat disease data were available from CropMonitor for all years except 1983 and 1984. The survey also provided information for the same crops on fungicide use, plus very limited information on cereal pests (summer aphids). Data on wider pesticide use were accessed from Pesticide Usage Survey reports, which were readily available back to 1998.

Foliar disease control

Both the incidence and severity (Figure 54) of septoria leaf blotch (*Mycosphaerella graminicola* or *Septoria tritici*) in treated farm crops have varied over the last 30 years. This will largely have been due to seasonal weather effects, in particular spring rainfall (affecting disease pressure and the ability to apply fungicides at the optimum timing), and to an extent changes in the varieties being grown. No trend towards increasing or decreasing Septoria levels is evident over the period as a whole. However, between the mid-1990s and early 2000s severity appears to have increased (if the highly unusual 2000/01 season is ignored), and then decreased again from the mid-2000s up to 2010. In addition to weather and variety effects, changes in fungicide dose, declining sensitivity to triazole fungicides and development of resistance to strobilurin fungicides in the late 1990s and early 2000s could have contributed to the patterns that are evident. The increase in severity from the mid-1990s coincided with the start of the yield plateau, so a short-term impact is possible.

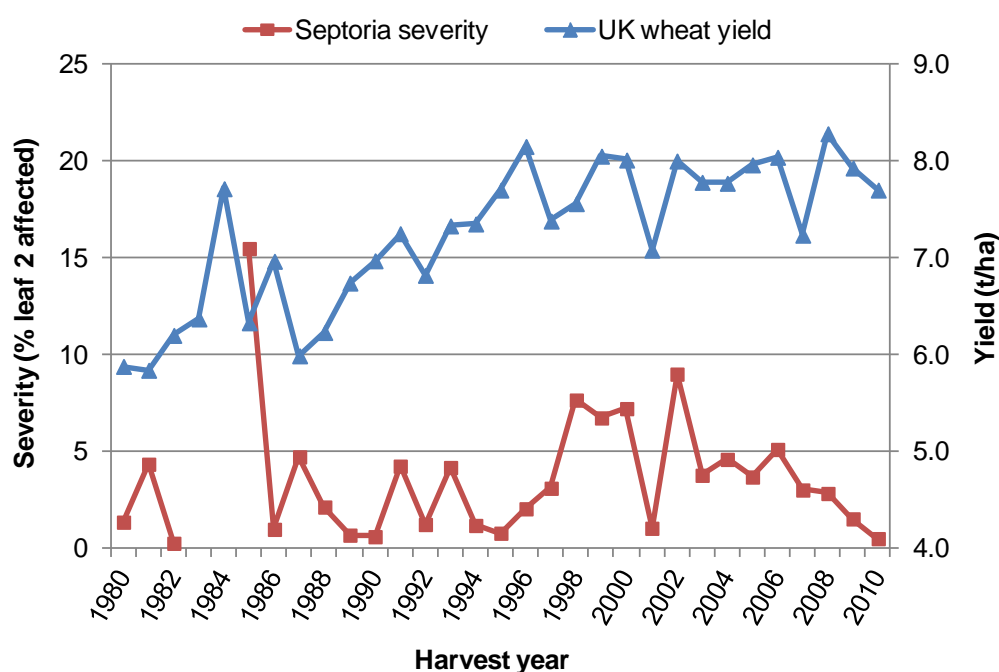


Figure 54. Average severity (% area of leaf 2 affected) of Septoria leaf blotch for commercially treated wheat crops in England.

The average area of leaf 2 affected by septoria in late June or early July (at about GS75) was 3% from 1980 to 1996 (2% if the extreme year of 1985 is excluded). The average area affected from 1997 to 2002 was 6%, but falling back to an average of 3% from 2003 to 2011. Assuming a yield loss of 0.4% for every 1% disease on leaf 2, it is estimated that yield losses due to septoria from 1997 to 2010 would have ranged from less than 0.5% to more than 3.5%, with an average annual yield loss of about 2% from 1997 to 2002 compared to 1% for 1980 to 1996 or 2003 to 2010. The national average yield loss is estimated to have increased from 1.4% (0.11 t/ha) in 1996 to 2.1% (0.17 t/ha) in 2002 but falling to less than 0.1% (<0.01 t/ha) in 2010. Clarke *et al.* (2009) estimated

the potential annual loss of wheat production due to septoria to be only 50,000 tonnes (0.3%) with current fungicide treatments.

The incidence of yellow rust (*Puccinia striiformis*) or brown rust (*Puccinia triticina*) in treated crops has varied substantially since 1980 (Figure 55), due to seasonal weather effects and changes in the susceptibility of varieties being grown (including the appearance of new races able to infect previously resistant varieties). From 1980 to 2010 brown rust incidence declined at a rate of 0.6% fewer crops affected per year, and yellow rust at a rate of 0.4% fewer crops affected per year. The peak for brown rust in 2007 can be explained by favourable weather and spread of a new race able to infect previously resistant and commonly-grown varieties. Even in years with higher incidence, the severity of rusts as recorded has remained low: below 0.1% of leaf 2 area for yellow rust and below 1% for brown rust (in all years except 2007). However, it is noted that for yellow rust peak disease severity will often occur before the end of June, so its impact has been under-estimated. The impact of the declining incidence of rusts on the national wheat yield trend is estimated at <0.001 t/ha per year. Clarke *et al.* (2009) estimated the potential annual loss of wheat production due to rusts to be about 85,000 tonnes (0.5%) with current fungicide treatments.

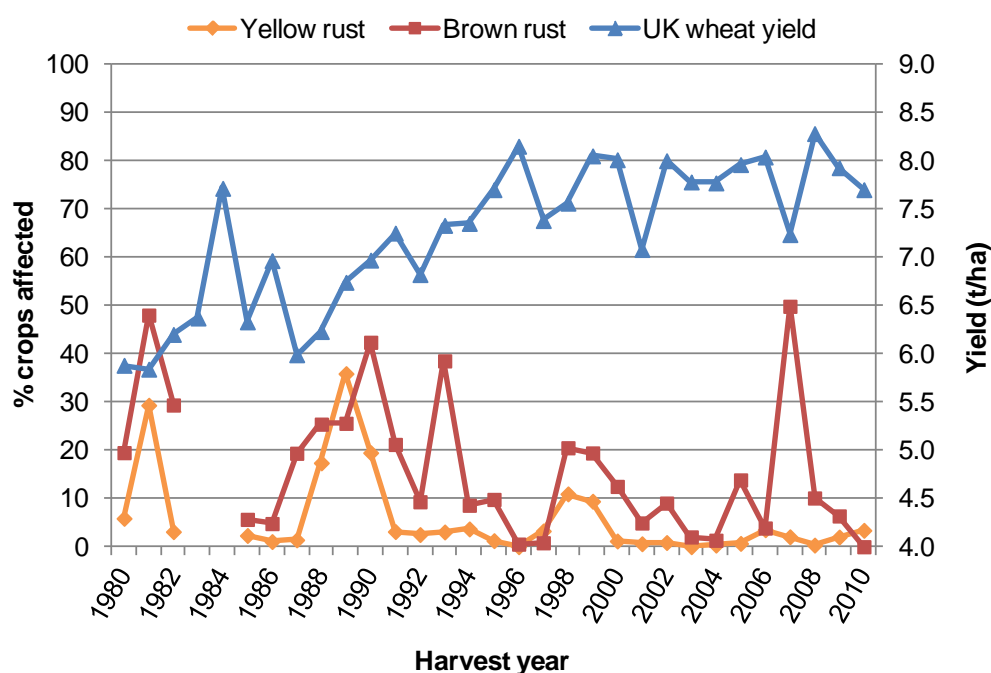


Figure 55. % of commercially treated wheat crops affected by yellow rust and brown rust in England.

The incidence of powdery mildew (*Blumeria graminis* f. sp. *tritici*), although equally variable, has tended to decrease since 1996, with severity always below 0.5% of the area of leaf 2. The incidence of tan spot (*Pyrenophora tritici-repentis*) has tended to increase since about 2002, having not been observed at all between 1996 and 2001. This recent increase may be linked to decreasing levels of Septoria. However, tan spot severity has always been below 0.1% of the area of leaf 2 affected. Neither disease is likely to have contributed to the plateauing of yields.

Stem and root diseases

Since the mid-1990s the proportion of stems affected by moderate or severe eyespot (*Oculimacula yallundae* and *O. acuformis*) has ranged from 5% to over 20% (Figure 56). A small disease peak occurred prior to 2000, but since then eyespot levels have remained relatively low, coinciding with the availability of a number of new fungicides with improved eyespot activity. Clarke *et al.* (2009) estimated the potential annual loss of wheat production due to eyespot to be about 86,000 tonnes (0.5%) with current fungicide treatments. Other than the disease peak that occurred early in the yield plateau period, no relationship between trends in eyespot levels and yields is apparent.

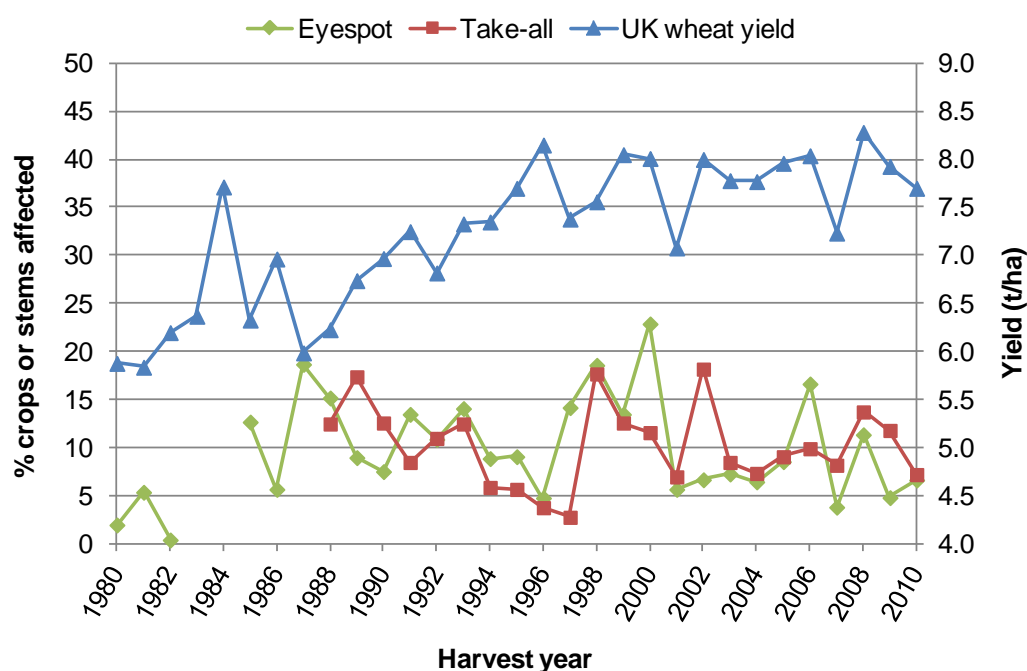


Figure 56. % of commercially treated wheat crops affected by moderate / severe take-all and % of stems affected by moderate / severe eyespot in England.

Between the late 1980s (when assessments began) and the mid-1990s, the incidence of moderate or severe take-all (*Gaeumannomyces graminis* var. *tritici*) decreased from about 15% down to 5% (Figure 56). This coincided with the period of relatively consistent yield improvement that occurred between the mid-1980s and mid-1990s, and may well have been a contributory factor. Assuming a 0.4% yield loss for every 1% of moderate or severe take-all (Hornby & Bateman, 1991; Schoeny *et al.*, 2001), it is estimated that average yield losses due to take-all would have fallen from 6% to 2% during that period. Since then take-all incidence has varied between 7 and 18%, with an estimated yield loss range of 3-7%. Clarke *et al.* (2009) estimated the potential annual loss of production due to take-all to be about 428,000 tonnes (2.5%) with current treatments. There is though very little indication of an increasing trend in take-all that could be contributing to a plateauing of yields.

Pest control

Pesticide Usage Survey data show that the area of wheat treated with molluscicides had increased from about 147K hectares (7% of the wheat area) in 1992 to about 259K hectares (13%) in 1998 and 882K hectares (43%) in 2008, although it had dropped back to about 400K hectares (21%) in 2010. Shirley *et al.* (2001) estimated the annual cost of slug damage in wheat at about £4M, compared to an estimated £2.7M in 1985 (Defra, 2010b). Clarke *et al.* (2009) estimated annual yield losses in wheat at 0.5% with current treatments. However, insufficient data were available to reliably estimate the impact of slug damage on the national wheat yield trend from 1980 to 2011.

The UK wild rabbit (*Oryctolagus cuniculus*) population was estimated to have risen to 37.5M by the early 1990s (Harris *et al.*, 1995), about 35-40% of the pre-myxomatosis level reached during the first half of the 20th Century. Assessments of the population trend since the mid-1990s differ, but according to Battersby (2005) survey evidence from three independent schemes rather surprisingly suggested a decline since the mid-1990s. Natural England estimate that farmers are losing £50M per year as a result of rabbit damage to cereals, with 1% yield loss per rabbit per hectare recorded for winter wheat (Anon, 2011), and a 20% yield loss (from 20 rabbits grazing per hectare) possible without an obvious crop height reduction at harvest. Although there are no data available to assess trends in the wheat area affected or grazing severity, with no apparent overall population increase since the 1990s there is insufficient evidence to link rabbit damage to recent yield stagnation.

Insufficient data were available to enable trends in aphid populations to be examined. A snapshot based on 3 years of assessments in the mid-2000s in farm crops that had not received a summer insecticide revealed average grain (*Sitobion avenae*) and rose-grain (*Metopolophium dirhodum*) aphid populations that were well below the economic threshold for treatment, and even in the worst year only a small proportion of crops where insecticide treatment would have been recommended. Summer aphids were considered by Clarke *et al.* (2009) to be resulting in negligible loss of national wheat production with currently available treatments. The same applied for orange wheat blossom midge (*Sitodiplosis mosellana*), although it was noted that in 1993 an outbreak was estimated to have caused a 4% reduction in the national wheat yield. According to Ellis *et al.* (2009) pesticide usage figures indicate that 12% of wheat crops are treated against orange wheat blossom midge, despite the sporadic nature of attacks. The potential annual loss of wheat production due to autumn aphids carrying BYDV was estimated at 140,000 tonnes (about 0.8%). However, there is little evidence (prior to autumn 2011) that this has increased in importance over the last 30 years.

The effect of nematodes on wheat crops had been suggested as a potential factor in stagnating yields. A recent survey of 25 cereal fields across southern Britain revealed that about 65% of samples were infested with cereal cyst nematodes, with most fields containing mixed populations of *Heterodera avenae* and *H. filipjevi* (Mitchinson, 2009). Although the presence of the former

species has been known for a long time and has declined in importance in the last 30 years due to naturally occurring fungal pathogens of the nematode, there was concern that *H. filipjevi* may be a threat to yields. However, this has been shown to be controlled by the same fungi as *H. avenae* and is not therefore considered a significant threat (Mitchinson, 2009). A number of species of root knot nematodes are found in north western Europe and can affect many crops, including cereals (mainly *Meloidogyne naasi*). The occurrence of damage has increased, and has been blamed on reductions in the use of certain pesticides, milder winters and warmer summer temperatures (Anon, 2008). Although there is no evidence to link nematodes to an impact on UK farm yields to date, climate warming means that this potentially increasing threat should not be ignored.

Weed control

No annual survey data were available to evaluate changes in weed populations over the last 30 years. However, Clarke *et al.* (2009) estimated potential annual yield losses due to several key species, based on currently available treatments and the proportion of the wheat area believed to be affected. Assuming that black-grass (*Alopecurus myosuroides*) affects 38% of the wheat area (Whitehead & Wright, 1989), and has an average population in affected fields of 10 black-grass plants/m² giving a treated yield loss of 4%, it was estimated that the current potential loss of wheat production nationally could be 260,000 tonnes (1.5%). The area of wheat affected by black-grass may have risen slightly since 1989, but it is more probable that the average number of black-grass plants/m² in treated fields would have increased over that time within the affected area (due to increasing resistance to, and decreasing availability of, herbicides). As relationships between weed populations and yield losses are variable it is difficult to put a value on the likely change over time. However, an increasing negative impact on the national wheat yield trend cannot be ruled out, and at very least this may have partly shifted the focus for some growers from management practices that optimise yield to strategies that enable black-grass control to be maintained.

Other weed species estimated by Clarke *et al.* (2009) to be responsible for annual yield losses of more than 100,000 tonnes (0.5%) each were cleavers (*Galium aparine*), annual meadow-grass (*Poa annua*) and rye-grass (*Lolium multiflorum*). Although affecting more than half of the wheat area, yield loss with current treatments was considered small for cleavers and annual meadow-grass, and there is little indication that these have been an increasing problem on farm. Rye-grass was estimated to result in similar treated yield losses to black-grass, but on a smaller area of the wheat crop, such that this is unlikely to have had a significant impact on the national yield trend.

Pesticide use

Information collected on crop management practice for the CropMonitor survey shows a steady increase in the proportion of crops treated with fungicides at the 'T0' (GS30) and 'T1' (GS32 or leaf 3) timings (Figure 57). The proportion of crops treated at the critical 'T2' (GS39 or flag leaf) timing

also increased up to the mid-2000s, but has since levelled-off. The 'T3' (ear spray) timing shows a slightly different trend, with a slight decrease in the proportion of crops treated between the early and late 1990s, which was not reversed until the late 2000s. Omitting the final T3 spray (in the expectation of limited benefit) was a common measure adopted by many growers in response to poor grain prices post 1996. Higher grain prices (along with increased emphasis on Fusarium control to reduce mycotoxins in grain) are likely to have driven the more recent increase in crops treated at T3. However, as the T1 and T2 timings normally have the greatest influence on wheat crop yield, there is little evidence to suggest that a significant adverse impact on the yield trend is likely to have occurred as a result of changes in the number of fungicides applied.

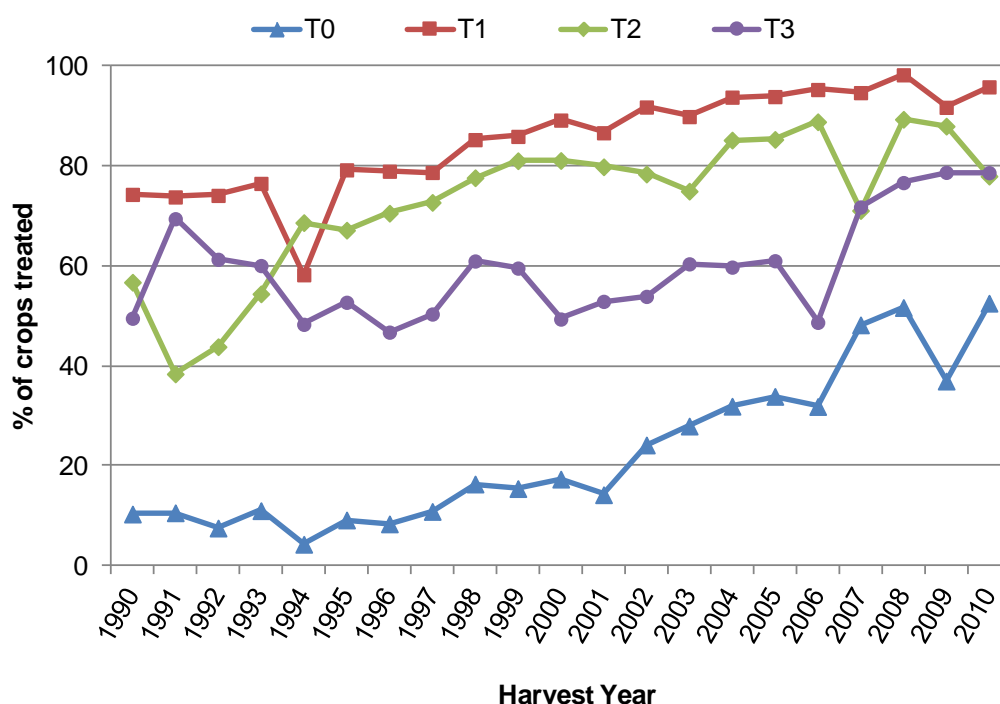


Figure 57. % of commercial wheat crops in England treated with fungicides at T0, T1, T2 and T3.

The average total dose of fungicide applied to wheat crops shows a steady decline between 1990 and 2002, and then a steep increase until 2008 (Figure 58). This has been followed by a slight decrease again, probably due to a succession of very dry springs resulting in very low disease pressure in parts of England. The decrease in fungicide dose between 1990 and 2002 was most likely a response to the introduction of new, more effective fungicides but also lower grain prices, with growers optimising inputs at slightly lower doses rather than omitting treatments completely. Knight *et al.* (2008) found that, when used in two-spray programmes in a mixture with strobilurin and/or chlorothalonil fungicides, the optimum total dose of the triazole fungicide epoxiconazole was 20-30% lower for a wheat price of £80/t than for a price of £160/t, giving an optimum yield that was 0.06-0.12 t/ha lower, in situations where septoria was the main disease.

At the time the industry was largely unaware that resistance was developing in septoria to the strobilurin group of fungicides and that its sensitivity to some triazoles was declining. However, the practical significance of these two developments had become clear by 2002, and growers and agronomists responded by increasing triazole fungicide doses to compensate for loss of strobilurin efficacy and the shift in triazole performance. As noted earlier, this response was perhaps a little later than it needed to be, contributing to the increase in septoria severity for a few years either side of 2000. An inadvertent contribution to stagnating wheat yields during that period is probable.

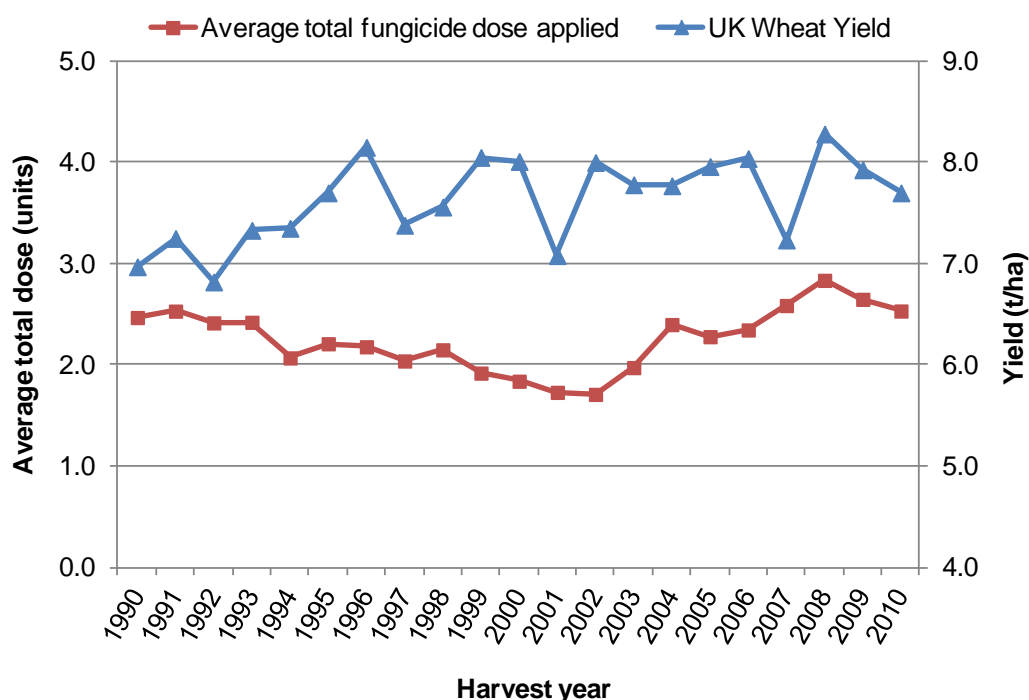


Figure 58. Average total fungicide dose (units) applied to commercially treated wheat crops in England.

Data from the Pesticide Usage Survey confirm an increase since 1998 in the average number of fungicide applications to wheat (Table 10). The number of herbicide applications has also increased since 2000, possibly reflecting the increasing problems caused by herbicide-resistant black-grass, which usually now requires at least one pre-emergence and one post-emergence treatment to achieve acceptable control, rather than just a single early-post emergence herbicide. The average number of insecticide applications increased during the mid-2000s, but has recently dropped back to below pre-2002 levels. This may in part be due to a rise in the proportion of crops being treated for orange wheat blossom midge, which was a mounting problem in the early 2000s but less so in recent years, aided perhaps by the growing number of midge resistant varieties.

Table 10. Average number of spray rounds applied to wheat crops in Great Britain.

Harvest year	1998	2000	2002	2004	2006	2008	2010
Group	Number of spray rounds applied to wheat						
Insecticides	1.1	1.0	1.3	1.5	1.4	1.3	0.8
Fungicides	2.8	2.8	2.8	2.9	3.0	3.5	3.4
Herbicides	2.4	2.5	2.8	3.1	2.8	3.0	2.7
PGRs	1.4	1.3	1.4	1.4	1.6	1.7	1.5
Molluscicides	0.1	0.4	0.4	0.1	0.3	0.6	0.3
All pesticides	5.3	5.5	5.8	5.9	5.9	6.5	5.9

The number of fungicide active ingredients has increased proportionately more than the number of applications, probably due to greater use of mixtures as an anti-resistance measure and to ensure robust disease control (Table 11). Similarly, use of herbicide products or mixes containing several active ingredients is more and more common as an anti-resistance measure and to combat rising grass weed populations. It is difficult to determine whether or not increasing herbicide use might indicate the potential for yield loss due to weeds to be rising, or provide reassurance that growers and agronomists are responding to prevent higher yield losses. Either way, it is well known that maintaining control of difficult weeds is as much a priority for some growers as optimising yield.

Use of Plant Growth Regulators (PGRs) on wheat has increased only marginally since 1998. Over the last 3 decades severe lodging has occurred on average once every 3 to 4 years. In a severe lodging year (1992) an aerial survey of nearly 3,000 ha of wheat revealed that an average 16% of the wheat area was lodged (Berry *et al.*, 1998). Yield losses in lodged patches can be anything up to 100% if they cannot be harvested, but more typically might be around 25%, such that in a severe lodging year the reduction in national yield could be as much as 4%. But there is no evidence to suggest that yield losses due to lodging have risen in the last two decades.

Table 11. Average number of active ingredients applied to wheat crops in Great Britain.

Harvest year	1998	2000	2002	2004	2006	2008	2010
Group	Number of active ingredients applied to wheat						
Insecticides	1.2	1.0	1.3	1.5	1.4	1.3	0.8
Fungicides	6.4	6.4	5.9	7.5	7.5	9.7	9.7
Herbicides	4.6	4.8	5.3	6.2	5.8	6.0	5.8
PGRs	2.2	2.1	2.3	2.2	2.5	2.8	2.4
Molluscicides	0.1	0.4	0.4	0.2	0.3	0.6	0.3
All pesticides	14.5	14.7	15.1	17.6	17.5	20.4	19.0

Farm Business Survey (FBS) data show that farms in the top wheat yield quartile are spending 20-25% more per hectare on pesticides than farms in the bottom quartile (Figure 59). The gap between the top and bottom quartiles has remained similar over the period analysed. The picture is different when comparing quartiles by gross margin (Figure 60). Farms in the top gross margin quartile were spending less on pesticides than farms in the bottom quartile in 2004 and 2005, although since 2007 differences have been quite small. This doesn't necessarily mean that farms in the top gross margin quartile have been using fewer pesticides (they may have been buying them more competitively) or that farms in the top quartile have limited their yields (they may have had a lower pesticide requirement, for example due to more timely application). However, it highlights that, prior to recent crop price improvements, the most appropriate level of investment in crop protection to optimise gross margin may have been less than that required to optimise yield.

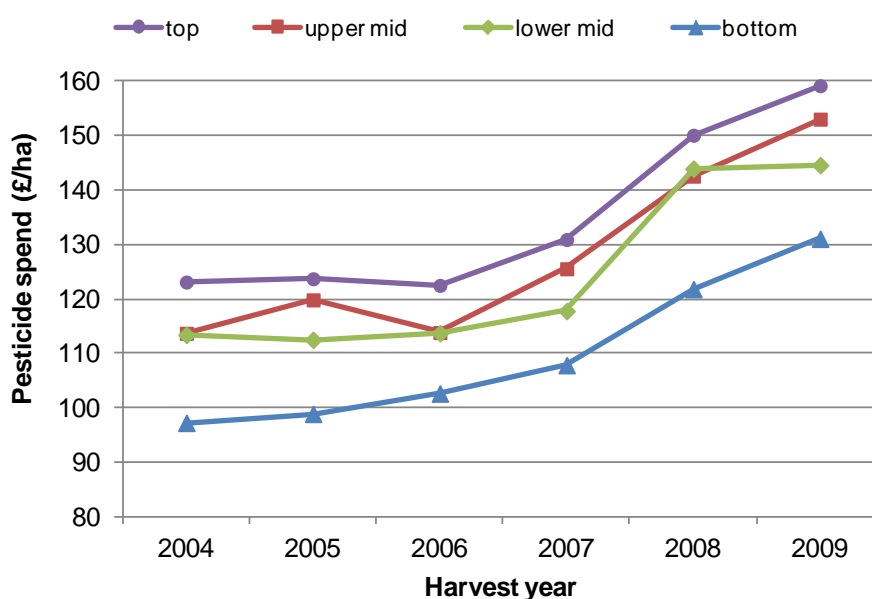


Figure 59. Pesticide expenditure for FBS top, upper & lower middle and bottom wheat yield quartiles.

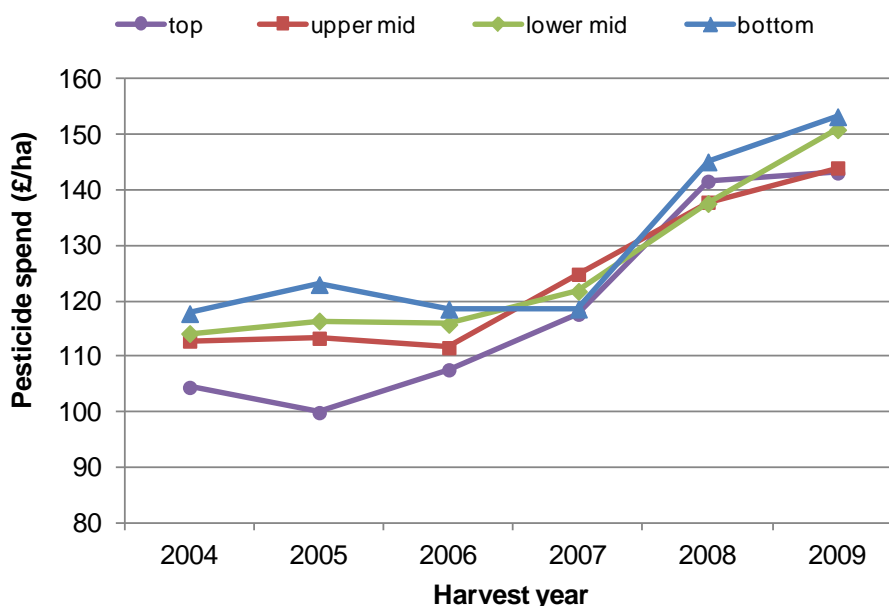


Figure 60. Pesticide expenditure for FBS top, middle and bottom quartiles for wheat gross margin.

3.4.10. Soil management and cultivations

Adoption of Minimum Tillage

Establishment of crops without conventional ploughing involves the use of non-inversion cultivators and/or specialist drills. There are fewer passes than conventional tillage, and it is shallower, which leaves most crop residues in the top 10cm (Morris *et al.*, 2010). This is referred to as minimum or reduced tillage. Another method of non-inversion tillage is no-till (also known as direct drilling and zero tillage). Crops are sown without any prior loosening of the soil by cultivation other than the very shallow disturbance (< 5cm) which may arise by the passage of the drill coulters and after which usually 30-100% of the surface remains covered with plant residues (Soane *et al.*, 2012). The main reasons for adopting minimum tillage or no-till are to reduce production costs and enable a greater area to be cultivated in a given time. This will be undertaken with the goal of maintaining or increasing yields (and margins) per unit area, but environmental benefits are also possible.

Lang (2009) estimated that, in the UK, minimum tillage is carried out on around 37% of cereal farms. Data from CropMonitor shows that the proportion of wheat crops established after ploughing increased from 60% to 90% between 1980 and the mid-1990s at the expense of reduced tillage. However, ploughing then decreased by the same amount between the late 1990s and late 2000s, and about 40% of crops are now established after reduced tillage (Figure 61).

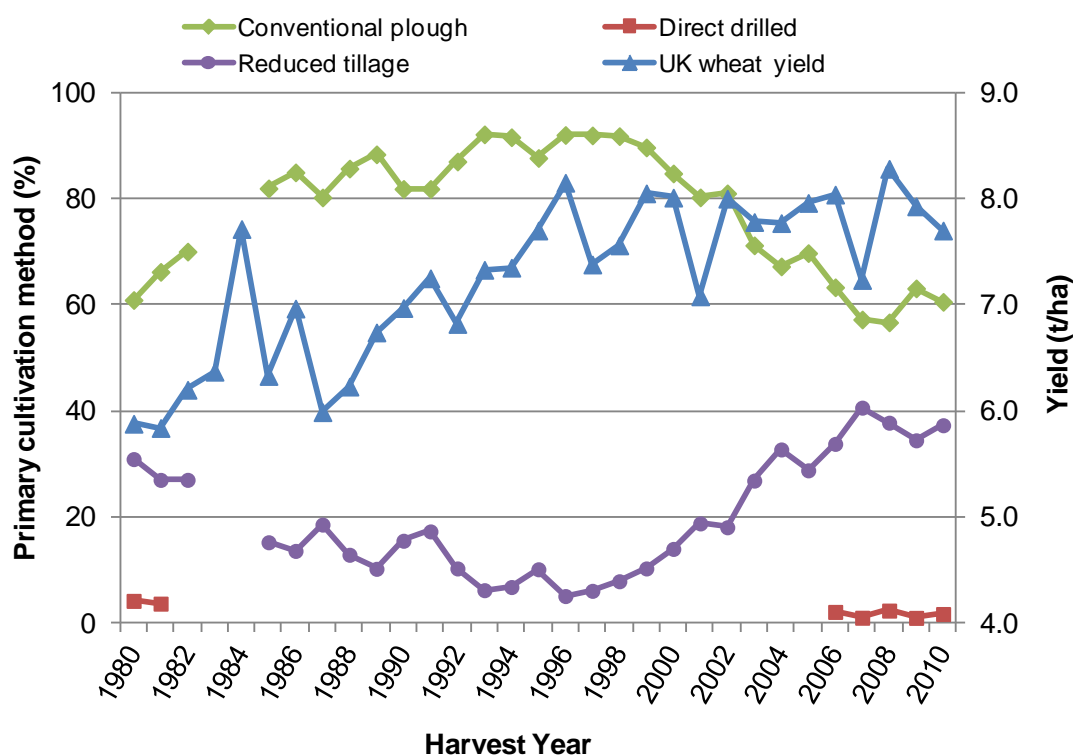


Figure 61. Proportion of winter wheat crops in England sown following conventional ploughing and reduced tillage, or by direct drilling.

HGCA produced two reports on the use of minimum tillage and no-till for cereals, one in 1988 and one in 2002. In the first report (Davies, 1988), a review of long-term experimentation totalling 200 site years revealed that well-managed reduced cultivation or no-till usually gave yields of winter cereals that were as good as or better than ploughing. Straw was either burnt or baled in these experiments and grass weeds were well controlled. Establishment of spring cereals by reduced tillage tended to be less satisfactory except where soil conditions were particularly good. In those situations where reduced tillage gave lower yields, greater populations of grass weeds and/or topsoil compaction or loss of surface structure were the causes. However, towards the end of the 1980s and into the early 1990s the ban on straw burning in England and the over-use of simple rotations which did not facilitate good weed control caused a decrease in the area of reduced tillage, particularly no-till (Christian, 1994).

The second report (Davies and Finney, 2002) revealed that farmers believed the use of large tractors and high work rates associated with minimum tillage could result in well-timed weed control through stale seedbeds and establishment of more of the crop at the optimum time and so would increase yields. However, the average farm size for those adopting minimum tillage is 60% larger than those not utilising this approach (Lang, 2009) and, as fewer farmers have sought to cover greater area with limited resource, the aspiration to utilise stale seedbeds and deliver timelier weed control can be compromised by the need to cover greater areas.

Machinery and chemical weed control have progressively improved since the early 1990s. One of the conclusions of the second HGCA report was 'It is clear from our review of evidence that labour and machinery costs of cereals can be reduced without compromising yields'. The top economic performing farmers produced consistently high yields at lower costs by use of minimum tillage. The report also stated that the link between tillage system and yield had 'always been tenuous' and that forecasting yield depressions from cultivation economies is 'difficult if not impossible'. Research is required to link yield to soil conditions that result from tillage, rather than directly with the tillage system. While some research (e.g. Stobart & Morris 2012) is starting to develop linkages between the outcomes of tillage, soil characteristics and yield, these links still need further development. Both HGCA reviews highlighted that the chances of yield loss or benefit from minimum tillage varied with location and farm size. The better situations were large cereal farms on well-drained clays, medium loams and chalk and limestone soils with annual rainfall of less than 630mm. In wetter areas only farms on well-drained light loams were considered suitable. Cultural measures for grass weed control, plus monitoring and control or reduction of compaction, were essential.

Evidence for effects of minimum tillage over a long period on crop yields is sparse. Nevertheless, fears of reduced yields under minimum tillage systems are still considered a constraint to the uptake of such systems in Europe (Jones *et al.*, 2006). A wider review of the impacts of reduced

tillage approaches on yield from a range of studies across Europe undertaken by Putte *et al.* 2010 found that reduced tillage approaches, on average, reduced yields by 4.5% across a range of crops. However, crop type, crop rotation, tillage technique and soil type all influenced the degree of reduction, and in cereals-only rotations relative yields under conservation tillage tended to decrease with time. In general reductions were around 4% for winter cereals and losses tended to decrease as tillage depth increased. The review also noted that when considering margins, slight reductions in crop yield can be offset through other savings.

Considering UK studies, a long-term experiment in Scotland showed no influence of tillage on yield trends over a 24-year period (Soane & Ball, 1998). The STAR project in East Anglia (Stobart and Morris, 2011) has evaluated the interaction between rotation and cultivation practices on a well-structured clay loam soil that is suited to non-inversion cultivation. Results over a 6 year period have indicated reductions of around 2% and 4% yield for deep (20cm depth) and shallow (10cm depth) non inversion approaches respectively compared to ploughing across the rotation, when considered across a number of rotational approaches.

For wheat crops alone across all rotations within the STAR project, when averaged over three years, yields were similar between plough, shallow and deep non inversion approaches. However, there was evidence of a yield penalty in the first year that all rotations were cropped with wheat, which was in the second year of the experiment (Table 12). This could be indicative of a yield reduction during the transition from ploughing to non-inversion, as has been reported by some growers, although it may equally just be a year effect. In the light of these comments, it may be asserted that with regard to wheat any influence of tillage on yield would be minor in the medium-long term provided that the technique used is suitable and that crop management can be maintained at a high standard. However, a larger impact in the short term cannot be ruled out.

Table 12. Wheat crop yields following non inversion tillage compared to ploughing. Mean of 4 crop rotations and 3 seasons (2007, 2009 & 2011).

Primary Cultivation	Mean winter wheat yield (% of ploughed)			
	2007	2009	2011	Mean
Plough	100	100	100	100
Deep non-inversion	89	107	109	101
Shallow non-inversion	86	106	108	100

Two scenarios were used to explore the potential yield effects of the shifts between plough and reduced tillage seen in the CropMonitor survey. The first, based on the STAR wheat data, assumed a 12% yield penalty for one year only (the transition year) on the area of land changing from ploughing to minimal tillage. The second assumed a continuing 3% yield penalty from minimal

tillage compared to ploughing, in line with the overall STAR data (and comparable with Putte *et al.*, 2010). The first scenario indicated a yield improvement of 0.001 t/ha per year between 1980 and 1996 as a result of increased ploughing, followed by a yield decline of 0.004 t/ha per year between 1996 and 2010 as a result of increased minimal tillage. The second scenario indicated an average yield improvement of 0.002 t/ha per year between 1980 and 1996, and then a yield decline averaging 0.007 t/ha per year from 1996 to 2010 (Figure 62).

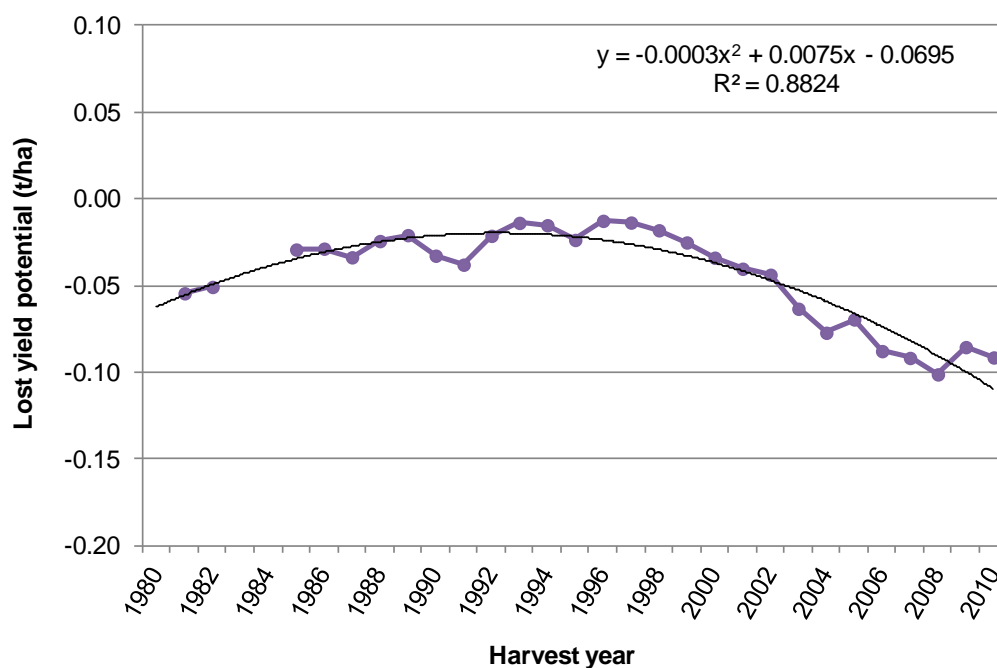


Figure 62. Estimated loss in wheat yield as a result of minimal tillage (compared to 100% ploughing), assuming that minimal tillage is 97% of ploughed yield on a continuing basis ($x = 1$ for 1980).

Soil compaction

Dobbie *et al.* (2011) observed that in Scotland there was no systematic assessment of the extent and wider implications of soil compaction. In the UK subsoil compaction is also a concern, but there is insufficient information to extrapolate data gathered from field experiments (Jones *et al.*, 2003). Subsoil compaction is a hidden problem that is cumulative and hard to quantify. Tractor and field machinery wheel loads have progressively increased over the past 3-4 decades to 5-6 tonnes as the norm. Such loads, irrespective of the tyres used, will induce very high stresses in deep soil horizons. Even under plough based systems, there is evidence of soil structural damage from heavy machinery. Subsoil can be considered as having two distinct layers: an upper part that often consists of a plough pan and may be broken by subsoiling, plus a deeper unloosened layer that is only disturbed by drainage operations such as mole ploughing (Alakukku *et al.*, 2003). Compaction of subsoil layers deeper than ~40-50 cm may remain for a long time and cause a long-term reduction in crop yields (Petersen *et al.*, 2010). A recent survey of soil physical properties in 100 arable fields in Scotland revealed a significant percentage (>33%) of them may be sub-optimal for root growth (Hallet *et al.*, 2010).

Research outside the UK has shown wheat yield increases of up to 6% in the absence of soil compaction (e.g. Koch *et al.*, 2008). UK based research undertaken by Chamen (2011) indicated that soil compaction from trafficking by farm machinery can reduce wheat and barley yields by an average of 16% compared with un-trafficked areas (Chamen also reported that further European studies have shown an average yield increase across crops of 21%). However, further effective research in the area of compaction control and reduction is still required (Godwin *et al.*, 2008).

Another impact of larger field and larger machinery over the last 30 years has been a widening of tramline spacings, with 24m now standard on most cereal farms, and 36m (or wider tramlines) not unusual on the largest farms. The increase in uptake of GPS guidance and auto-steer devices over the last 10 years should also be contributing to improved accuracy, with the potential for a small positive impact on yields through reduced wheelings and overlaps, plus more efficient turning on headlands.

Under-drainage

According to the 2012 Defra Farm Practices Survey for England about 37% of the total managed land area has artificial under-drainage. The 2008 Farm Practices Survey showed that only 13% of cereal farms had no land at all with under-drainage, and 50% of cereal farms had at least half of their land under-drained. The 2012 survey revealed that, on cereal farms, 42% of under-drained land has been mole drained, with 45% of that repeat mole drained every 1-5 years and 40% every 6-10 years. While channels in soils such as chalky boulder clays can remain effective for at least 10 years, 15% of under-drained land is potentially being mole drained less often than it should be. However, the proportions of drained land affected by drain failure, soil damage due to seasonal water-logging or yield reduction due to sustained water-logging were all reported as less than 3%.

A recent article (FWI, 2012) highlighted the impact of failing drainage systems on farm, including reduced timeliness due to the inability to travel on land at the optimum time. Improvements to land drainage were considered by one grower to have contributed to increasing yields. No data could be found relating to trends in the drainage of wheat-growing land. However, an effect on the national wheat yield is possible, and a more comprehensive study of the state of land drainage is needed.

Soil organic matter

Soil organic matter (SOM) content is a key indicator of soil health and fertility, as it affects the soil's structure, workability, water holding capacity, drainage, pH, cation exchange capacity and ability to supply nutrients. Maintaining SOM content at an adequate level can be important in buffering crop yield variation, especially under extreme weather conditions, largely through improved rooting. Cultivation, notably deep ploughing, reduces SOM content through enhancing mineralisation,

leading to gradual degradation of the soil at least until equilibrium is reached, where the addition of SOM from the crop matches the losses through mineralisation. The 'active fraction' (decomposing organic matter) is more responsive to changes in crop or soil management than the more stable humus. It is estimated that the mean soil organic carbon content (SOC) of arable land in England & Wales decreased from 3.3% in 1980 to 2.8% in 1995 (Rusco *et al.* 2001). Given that the climate in the UK should be favourable for accumulation of SOC it was concluded that the decline has been the result of cultivation (especially of organic soils) and land use change (from grassland to arable).

Long-term trends in crop yields from experiments conducted since 1843 at Rothamsted show that, as yield potential has increased, yields have often been larger on soils with higher organic matter (Johnston *et al.*, 2009). However, it has equally been observed that SOM is higher where yields are higher. For continuous barley, annual applications of 35 t/ha farmyard manure (FYM) have resulted in a SOM content of 6.16% compared to 1.74% for plots receiving inorganic fertilisers. For continuous winter wheat, the equivalent values are 4.87% and 1.93% respectively. The yield advantage to FYM treated plots has been higher for barley than for wheat, and as the yield potential of wheat varieties increased between the 1970s and 2000s the amount of inorganic N fertiliser required on FYM treated plots (in order to match or exceed the yields of plots receiving inorganic fertilisers only) has also increased. A comparison on a sandy loam soil with two levels of SOM (1.3% and 3.4%) showed a yield advantage to higher SOM for spring barley regardless of the rate of fertiliser N applied, but no advantage to higher SOM for winter cereals (Johnston, 2011).

Results from these long-term experiments do not provide any evidence that the decline in mean SOM content observed from 1980 to 1995 is likely to have contributed directly to the plateauing of national wheat yields observed since 1996, assuming that supply of N, P and other crop nutrients has remained optimal. However, there are undoubtedly benefits to maintaining an adequate SOM content, and there are reports of farms where it is considered that even the incorporation of straw and other crop residues has increased average yields through improving the performance of poorer fields or areas.

3.4.11. Rotations

The CropMonitor survey underlines the steep decline in wheat crops sown following another wheat crop, between the late 1980s and mid-1990s (Figure 63). This coincided with a sustained and rapid increase in the national wheat yield, and was undoubtedly an influencing factor. The proportion of second or subsequent wheat crops had fallen from around 50% in the mid-1980s to 30% by the mid-1990s, and then 25% by the late 2000s. Initially the decrease in wheat following wheat or other cereals was the result of an increase in a number of break crops, including peas / beans, oilseed rape and later set-aside. The proportion of wheat crops after peas / beans has not risen beyond about 15% since the mid-1990s, whereas wheat following oilseed rape has continued to increase

steadily to 30% in the late 2000s, compared to around 10% in the 1980s. The increase in oilseed rape has occurred at the expense of a range of cereal and break crops, and through the withdrawal of set-aside. There is little evidence of a substitution of oilseed rape for peas / beans as a previous crop, unlike in France where this has been identified as contributing to wheat yield stagnation.

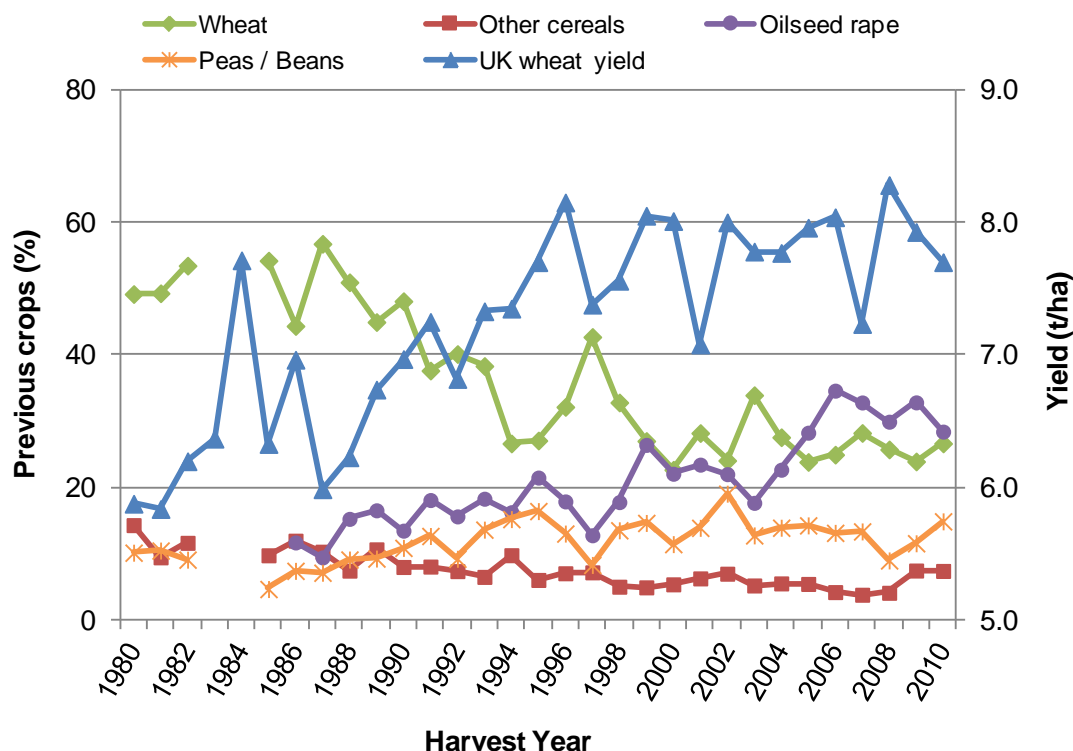


Figure 63. Proportion of wheat crops in England sown following wheat, other cereals, oilseed rape or peas/beans.

Table 13 shows mean yields over a 5 year period from 2006 to 2010 for winter wheat sown in first, second and third or subsequent wheat situations in a replicated rotational experiment on a single site on a sandy loam over clay soil in Norfolk. The break crop prior to the first wheats was oilseed rape in all cases, with first wheats sown in mid-late September and other wheats in mid-October, to reflect best farm practice for minimising take-all impact. The second wheat yield penalty averaged about 1 t/ha (or 10%), and the penalty for third or subsequent wheats was about 1.4 t/ha (14%). It is assumed that at least some of the yield penalty will have been due to increased take-all levels.

Table 13. Mean grain yields for 1st, 2nd and 3rd + winter wheat situations (Source: HGCA project 2922).

Crop Sequence	Yield (t/ha)	Yield (%)
1 st Winter Wheat	9.51	100
2 nd Winter Wheat	8.46	90
3 rd + Winter Wheat	8.10	86

Assuming that second or subsequent wheats on average yield 12% less than wheats following other crops (Table 14), it is calculated that the reduction from 50% to 30% could explain 0.16 t/ha (13%) of the 1.2 t/ha yield improvement observed between mid-1980s and mid-1990s, with the yield penalty (compared to 100% first wheat) decreasing from 0.44 t/ha to 0.28 t/ha, equivalent to 0.015 t/ha per year (Figure 64). Although this is based on data from a single experiment, over several seasons, it is consistent with results from other experiments (e.g. Vaidyanathan et. al, 1987). There was also a slight decline in the proportion of wheat crops sown following other cereals, from around 10% to nearer 5% by the late 1990s.

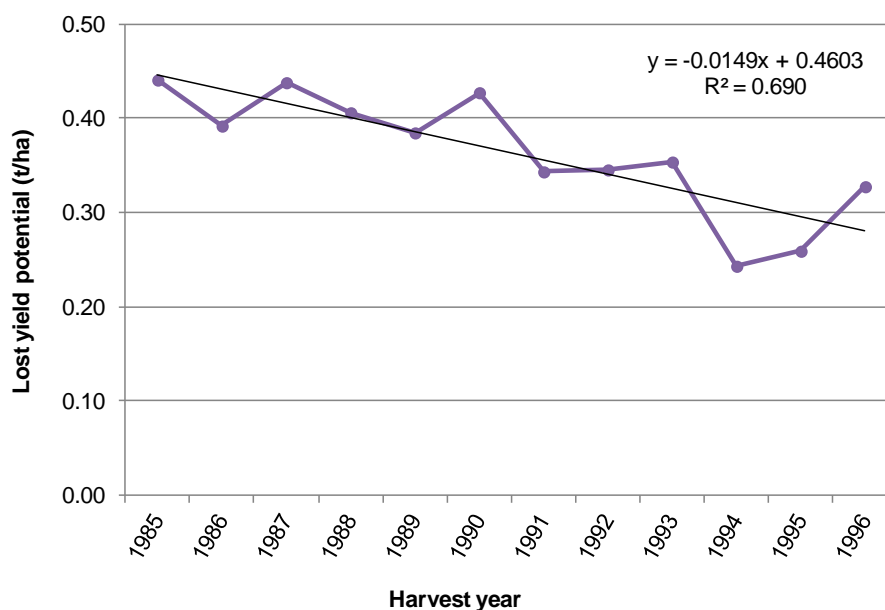


Figure 64. Decline in calculated loss of national yield potential as a result of decreasing proportion of second or subsequent wheat crops between 1985 and 1996 ($x = 1$ for 1985; $P < 0.001$; SE slope 0.0032, intercept 0.0233).

Results from a replicated and phased crop sequence experiment conducted by NIAB TAG on a shallow brash soil in Gloucestershire show that, over a 5 period year period from 1991-1995, yields of first winter wheats (Figure 65) following oilseed rape were marginally higher than those following combining peas, which were in turn slightly higher than after field beans or linseed (Overthrow, 2012). The mean yield advantage to wheats following a break compared to continuous was 23%. These results do not support the observation from France that wheat yields tend to be higher when following peas than oilseed rape. This could be explained by differences in the amount of N applied to the oilseed rape. However, wheat yields after beans were lower than after peas or oilseed rape. The decrease in area of peas and tendency for them to be substituted with field beans (Figure 66) may therefore have had a very small impact on the yields of wheat following pulse crops on farm.

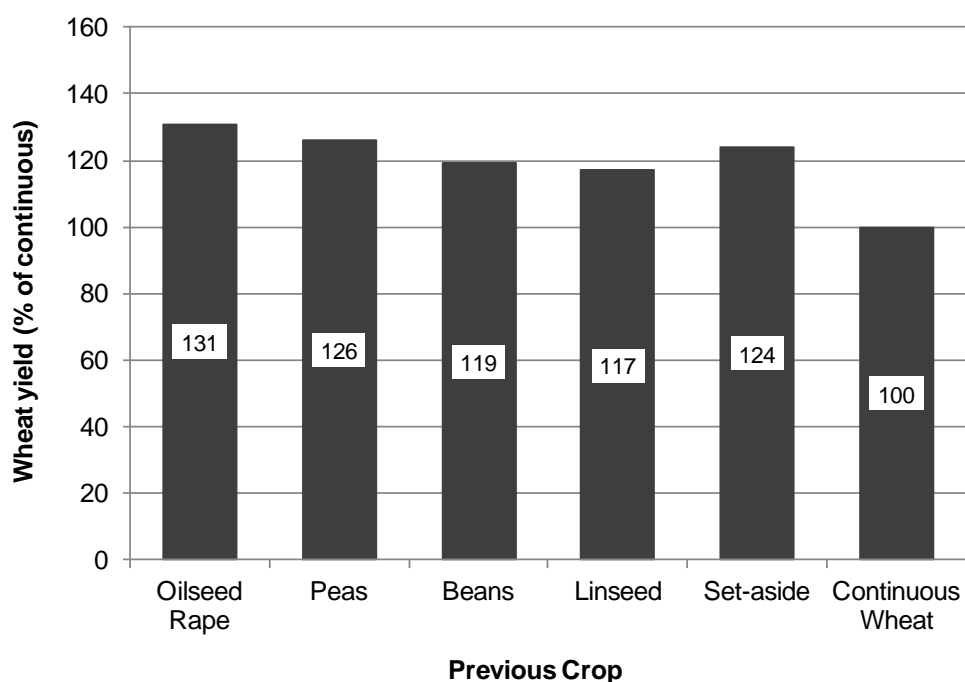


Figure 65. Yields of first wheats following a range of break crops, relative to continuous wheat.

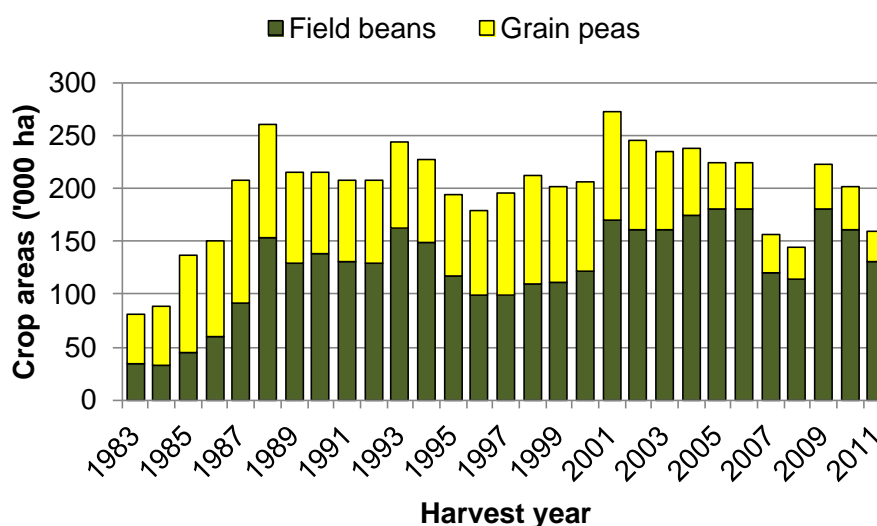


Figure 66. Combined areas of grain peas and field beans grown in the UK (Source: Defra).

In the same experiment, yields of first winter wheats after a single or double break were compared. Single break crops were oilseed rape, peas, beans and linseed. Double breaks were oilseed rape after peas (and vice versa), and beans after linseed (and vice versa). Both were preceded by wheat. In one year wheat yields were higher after the double breaks, but in the other they were higher after the single breaks. Averaged over the two years, there was little difference in wheat yields for single compared to double breaks (Richard Overthrow, personal communication).

The yields of first winter wheats have been compared to continuous wheat when grown in alternating rotations with winter break crops (winter oilseed rape and winter field beans), spring break crops (spring field beans and spring oats) or fallow (with mustard cover crop) in a large scale

replicated field experiment on a heavy clay soil in Suffolk (Table 14). Each rotation has been examined under plough, deep and shallow non-inversion and 'managed' (annually determined) cultivation systems. Averaged over the three harvest years (2007, 2009 and 2011) and four cultivation systems, mean yields of first winter wheats in rotation with winter breaks and spring breaks have been very similar, but marginally higher than for first wheats in rotation with fallow. All three sequences have given substantially higher yields than continuous wheat.

Table 14. Mean grain yields for winter wheat in alternating rotations with fallow, winter and spring break crops, compared to continuous wheat (Source: NIAB TAG / Felix Cobbold Trust STAR project).

Crop Sequence	Yield (t/ha)	Yield (%)
Continuous wheat	5.72	100
First wheats alternating with winter break crops	8.79	157
First wheats alternating with spring break crops	8.76	156
First wheat alternating with fallow / mustard	8.57	153

The proportion of wheat crops following set-aside averaged 7% between the mid-1990s and early 2000s. Not all of the set-aside will have been managed as fallow with a mustard cover crop as in the STAR project. But as an estimate a yield penalty of about 0.2 t/ha may have been incurred on about 5% of the national wheat area, equivalent to an overall yield reduction of just 0.01 t/ha.

3.4.12. Sowing dates and seed rates (crop establishment)

Success of crop establishment is determined by many factors, including cultivation method, soil conditions, sowing date, seed rate, prevailing weather and the effects of pest. It is not easy to examine trends over time in establishment per se, and there are no data available. This section focuses on sowing date and seed rate, with trends in other factors covered previously.

CropMonitor highlights the shift in sowing dates for wheat that has occurred over the last 30 years (Figure 67). The greatest change occurred from 1995 onwards, with the proportion of wheat crops sown before 1st October increasing from an average of less than 20% in the 1980s and early 1990s to nearly 40% in the late 1990s and 2000s. This was half at the expense of crops sown in the former main sowing period for winter wheat (1st - 20th October) and half at the expense of 'late sown' crops (after 21st October). The reduction in wheat as a previous crop and replacement by oilseed rape will have facilitated this move to earlier sowing, through the reduced risk of take-all, as will the shift from ploughing to non-inversion cultivation (allowing land to be prepared more rapidly).

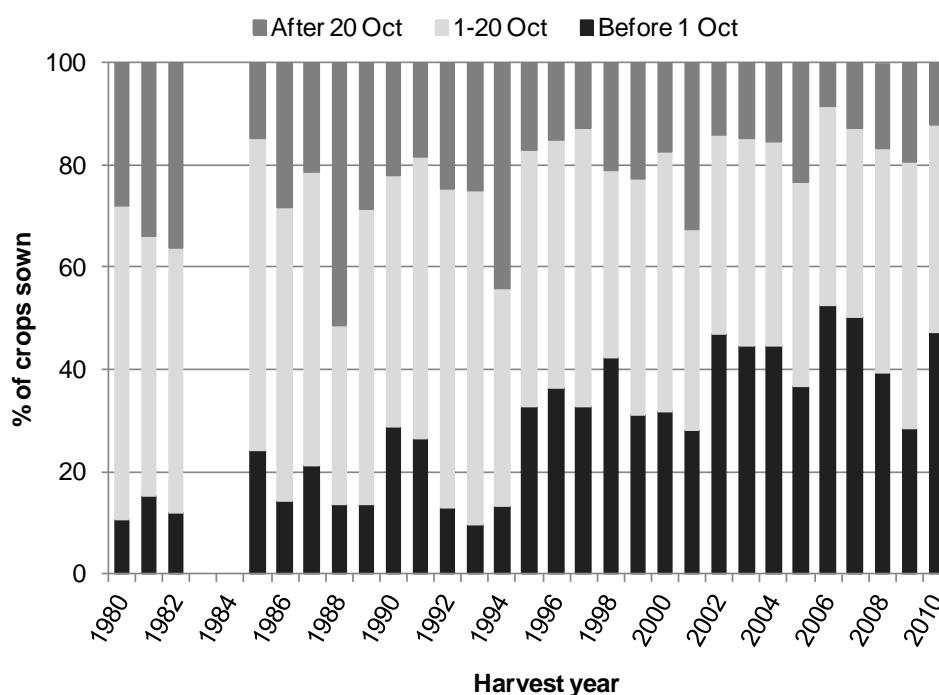


Figure 67. Proportion of wheat crops in England sown before 1st October, between 1st and 20th October and after 20th October.

An unpublished analysis of NIAB TAG trials at 4 locations in England and over 5 harvest years from 1999 to 2003 compared the average yields of 6-10 varieties when sown on different dates in separate replicated variety trials but located in the same field and receiving similar inputs. Table 15a compares yields for 'early' (1st - 10th Sept) and 'conventional' (20th Sept – 10th Oct) sowing dates, and Table 15b compares yields for 'conventional' and 'late' (25th Oct – 15th Nov) sowing dates. The average yield advantage to 'early' sowing was 1.4%, and the average yield penalty to 'late' sowing was 3.7%. There have been many other studies that have examined the effects of sowing date on wheat yield (e.g. Milford *et al.*, 1993; Green & Ivins, 1985) in which the advantages to September sowing have been variable.

Table 15a. Yield impact of early (1st – 10th Sept) sowing of winter wheat varieties compared to sowing at the conventional (20th Sept – 10th Oct) timing (Source: NIAB TAG).

Average yield advantage to early (1 st -10 th Sept) sowing compared to conventional (20 th Sept – 10 th Oct) sowing	+1.4%
Proportion of comparisons where early sowing was more than 5% higher yielding	37%
Proportion of comparisons where yields of early and conventional were within 5% of one another	37%
Proportion of comparisons where early sowing was more than 5% lower yielding	26%

Table 15b. Yield impact of late (25th Oct – 15th Nov) sowing of winter wheat varieties compared to sowing at the conventional (20th Sept – 10th Oct) timing (Source: NIAB TAG).

Average yield penalty to late (25 th Oct -15 th Nov) sowing compared to conventional (20 th Sept – 10 th Oct) sowing	-3.7%
Proportion of comparisons where late sowing was more than 5% lower yielding	50%
Proportion of comparisons where yields of late and conventional were within 5% of one another	38%
Proportion of comparisons where late sowing was more than 5% higher yielding	12%

In a reanalysis of NL/RL data for spring type wheats, trials were grouped by month of sowing, the effects of month, year and variety estimated and a linear regression fitted to the month effects (Ian Mackay, personal communication). This showed a linear decrease in yields with sowing date from October to April of 0.58 t/ha per month (or 0.51 t/ha if October was excluded due to there only being a single trial). This is slightly greater than the estimated late sown penalty of 3.7% from the NIAB TAG trials. The analysis of 2002 - 2011 RL data reported in section 3.4.7 indicated a large divergence in wheat yield trends for 'early' and 'late' sown trials, but this may be attributable to differences in the years, sites, varieties and sowing dates compared.

Although the date bands for the NIAB TAG trials don't quite match the farm sowing dates from CropMonitor, as a rough guide, assuming that crops sown before 1st Oct on average yield 1.4% more than those sown between 1st and 20th Oct, and that crops sown after 20th Oct on average yield 3.7% less than those sown between 1st and 20th Oct (Tables 15a and 15b), it is calculated that the trend towards earlier drilling indicated in Figure 67 would equate to a yield gain of less than 0.1 t/ha between 1980 and 2010, or about 0.003 t/ha per year (Figure 68).

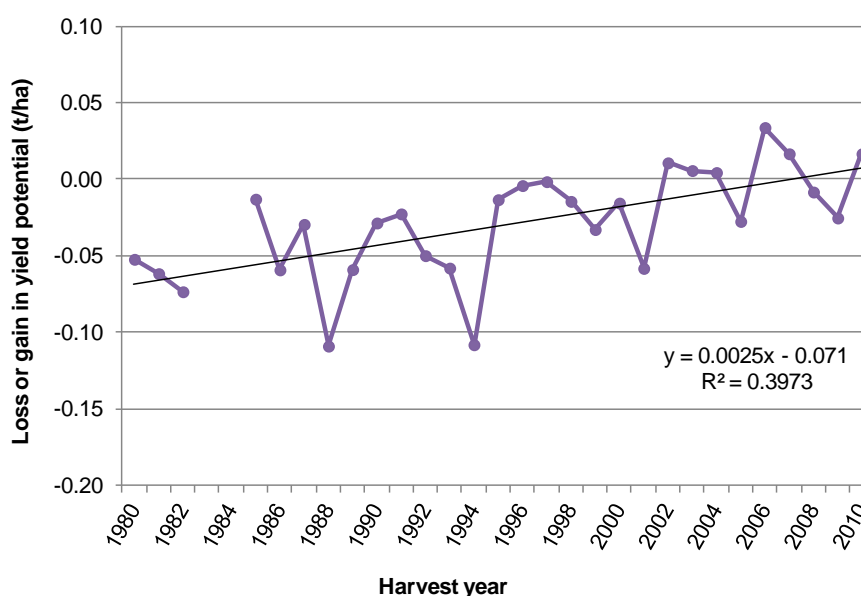


Figure 68. Calculated improvement in national yield potential as a result of earlier sowing of wheat crops between 1980 and 2010 ($x = 1$ for 1980; $P < 0.001$; SE slope 0.0006, intercept 0.0113).

It has been suggested that the tendency towards shorter rotations involving more frequent wheat crops e.g. alternating winter wheat and oilseed rape, combined with the move towards earlier sowing, could be causing an increase in take-all levels within first wheat crops in recent years. However, the CropMonitor survey does not indicate a trend towards increasing levels of moderate or severe take-all that are likely to have a significant impact on yield.

Advice on seed rates and plant populations for winter wheat changed from 1996 to 2011. As a result of HGCA Project 234 (Spink *et al.*, 2000), new advice was issued to growers on target spring populations (HGCA Topic Sheet No. 36, 2000). Targets were given as 62 plants/m² for crops sown by late September, 90 plants/m² for mid-October and 140 plants/m² for mid-November, with a recommendation to increase slightly for crops grown in northern Britain. Suggested seed rates were indicated to be 25-50% higher, so 80-90 seeds/m² for September, 120-130 seeds/m² up to October and 180-200 seeds /m² up to mid-November. It was indicated that most growers at that time were sowing 325-400 seeds/m² with a target spring plant population of 275 seeds/m².

Project 234 was based on results from two sites. Subsequently Spink *et al.* 2005 reported a further study (HGCA Project Report 361) in which results from six sites, and various agronomic factors, were examined. Optimum plant populations were found to be similar to, or slightly higher than, previously, ranging from 70 plants/m² for September sowing in southern England to 250 plants/m² in Scotland. The main interaction with agronomy was for rotational position, with optimum plant populations 30-40 plants/m² lower for rotational positions where take-all occurred compared to first wheats, or 20-25 plants/m² lower where a take-all seed treatment was used.

Tables 16a and 16b summarise unpublished NIAB TAG results from two series of first wheat seed rate experiments. The first series (Table 17a) includes four experiments sown in early October with between 1 and 3 varieties, conducted on shallow soils in southern and eastern England between 1997 and 2003. The second series (Table 17b) includes six experiments sown in late September or early October with a single variety, conducted on clay loam soils in central and eastern England between 2003 and 2006. It is estimated that the target population of 90 plants/m² indicated above for crops sown by mid-October would have resulted in an average loss of potential yield of about 1.0 t/ha for the shallow soil experiments and 0.5 t/ha for the clay loam experiments.

Table 16a. Mean winter wheat plant populations and yields obtained with four seed rates on shallow soils in England between 1997 and 2003. 8 comparisons over 4 experiments (Source: NIAB TAG).

Shallow soils 1997 – 2003	Seed rate (seeds/m ²)			
	100	200	300	400
Plant population (plants/m ²)	75	136	179	235
Yield (t/ha)	6.36	7.46	7.73	7.90

Table 16b. Mean winter wheat plant populations and yields obtained with six seed rates on clay loam soils in England between 2003 and 2006. 6 comparisons over 6 experiments (Source: NIAB TAG).

Clay loam soils 2003 – 2006	Seed rate (seeds/m ²)					
	75	150	225	300	375	375
Plant population (plants/m ²)	51	96	148	174	200	221
Yield (t/ha)	9.32	10.18	10.45	10.44	10.51	10.53

Spink *et al.* (2005) reported that many growers had reduced seed rates. However, in recent years, with drier springs leading to thinner canopies, lower ear populations and very little lodging, farm seed rates have tended to increase again slightly. This is especially true on heavy land affected by black-grass, in order to maximise the competitiveness of the crop and minimise gaps in the canopy in which grass-weeds can flourish. With conflicting results from field experiments, and no survey data available to examine trends in average farm seed rates over time, their overall impact on the national wheat yield trend is uncertain. However, it is evident that the target plant populations and suggested seed rates advised in the early 2000s may have been sub-optimal for yield in some situations, and could have had a small negative impact on the wheat yield trend at that time.

Case study evidence

Previous crops and sowing dates for wheat were compared for two of the case study farms that had rather different yield trends for wheat, between 1996 and 2011. Both farms are in Norfolk, and growing winter wheat and sugar beet on mainly medium texture soils. The first farm (Norfolk 1) is currently growing about 625 hectares of winter wheat within a total cropped area of 2100 hectares. A significant area of oilseed rape was introduced into the rotation, and the farm switched from ploughing to mainly deep non-inversion tillage, in 2003/04. The second farm (Norfolk 2) is much smaller, currently growing about 100 hectares of winter wheat within a total cropped area of about 200 hectares. A small area of oilseed rape was introduced, and the farm switched from ploughing to mainly deep non-inversion tillage, only recently in 2009/10.

The first farm has achieved an increase in wheat yields from about 8.5 t/ha to 10.5 t/ha since 1996, at an average rate of about 0.15 t/ha per year. The rate of increase has been more rapid, albeit rather erratic, since 2003 when the wheat following wheat was phased out of the rotation and a

significant area of oilseed rape introduced (Figure 69). Also around 2003, the proportion of wheat sown before 1st October increased to nearly 90% (Figure 70), facilitated by the change in rotation and the switch from ploughing to non-inversion tillage. Only a small proportion of wheat has been drilled after 20th October since then, mainly following sugar beet. For later-harvested sugar beet crops, where conditions may not be ideal for establishing wheat, spring barley is sown instead.

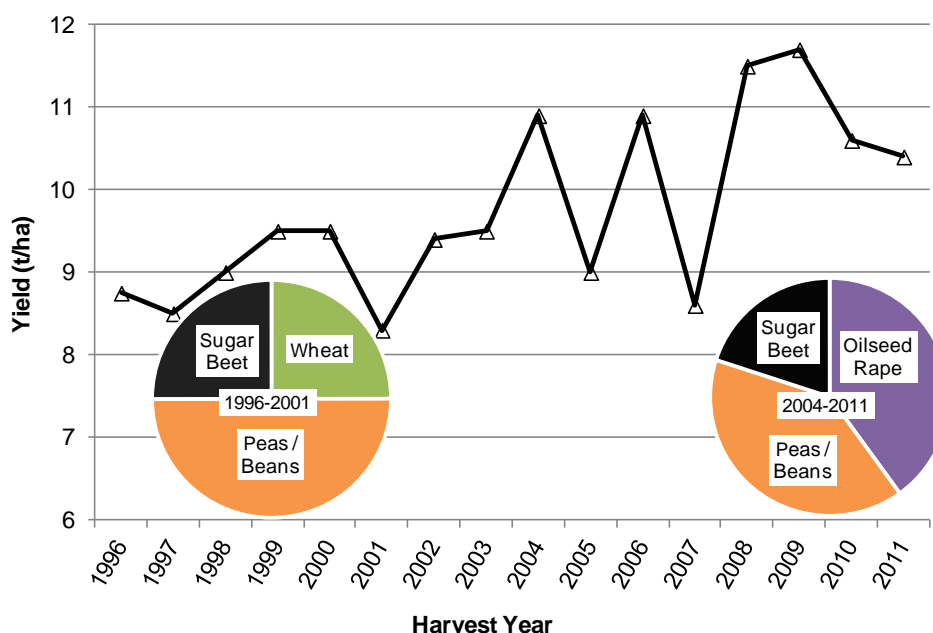


Figure 69. Winter wheat yield trend for the Norfolk 1 case study farm (line graph), and associated changes in proportion of crops preceding wheat for 2004-2011 compared to 1996-2001 (pie charts).

The second Norfolk farm saw a slight increase in winter wheat yields between the mid-1990s and mid-2000s from a base of about 8.0 t/ha, but a reduction since 2005, with the net effect equivalent to an overall decline of about 0.1 t/ha per year between 1996 and 2011. In 2005 wheat following wheat was dropped from the rotation and wheat after fallow introduced (Figure 71). However, since 2009, wheat after wheat has been reintroduced and some after oilseed rape, at the expense of fallow and to some extent sugar beet. Sowing dates for wheat have changed relatively little between 1996 and 2011, with just a small increase in the proportion sown before 1st October.

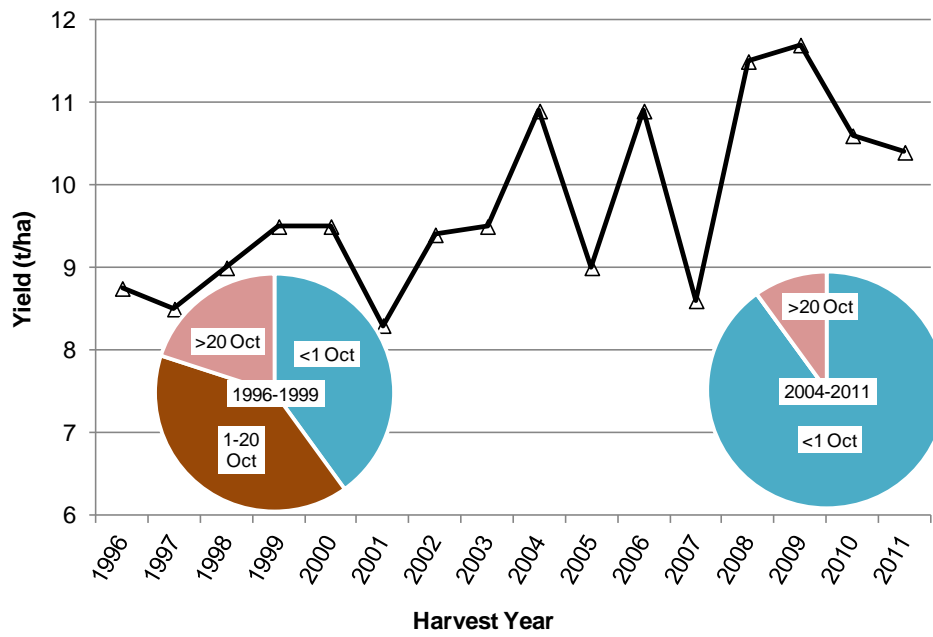


Figure 70. Winter wheat yield trend for the Norfolk 1 case study farm (line graph) and associated changes to wheat sowing dates for 2004-2011 compared to 1996-1999 (pie charts).

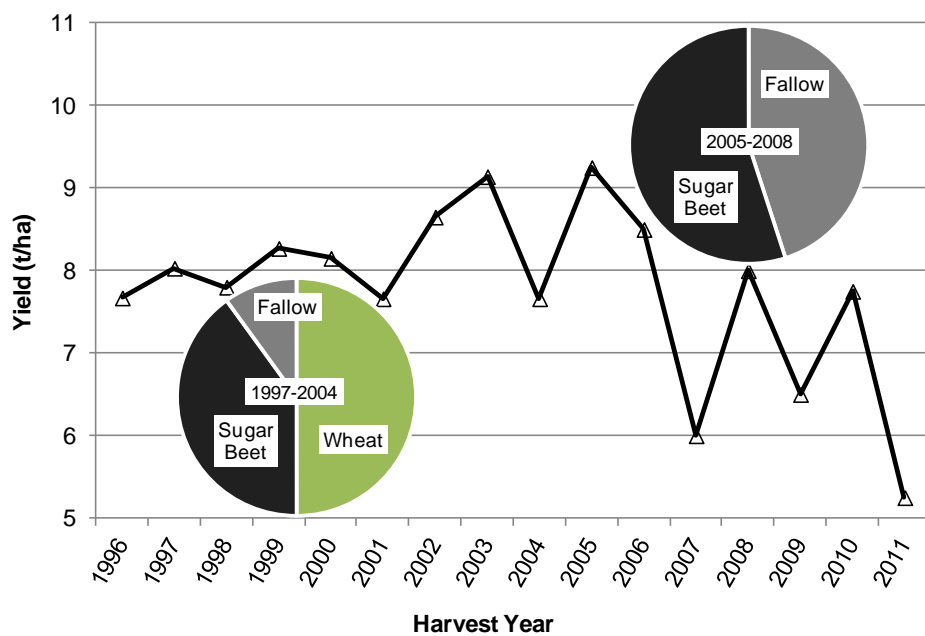


Figure 71. Winter wheat yield trend for the Norfolk 2 case study farm (line graph) and changes in proportion of crops preceding wheat for 2005-2008 compared to 1997-2004 (pie charts).

3.5. Results: Oilseed rape

3.5.1. Literature review

Global oilseed rape yield trends

Oilseed rape or rapeseed is produced extensively throughout the world. Four brassica species are commonly grown. The winter form of *Brassica napus* (Swede rape) is the most widespread in Europe and China (Berry and Spink, 2006). In the cooler high latitude areas of Europe and Canada the summer form of *B. napus* or winter and summer varieties of *B. rapa* (Turnip rape) are grown (Berry and Spink, 2006; Peltonen-Sainio *et al.*, 2007) *B. juncea* (Indian mustard) is common in India and parts of China, whilst *B. carinata* (Ethiopian mustard) is grown in NE Africa.

The largest producers of oilseed rape are China, Canada and India who between them accounted for 53% of the world's total production in 2010 (FAO statistics, 2012). Collectively, European Union (EU) countries contributed 34% of the total, with Germany, France, the UK and Poland being the major producers. In 2010 the UK was ranked sixth in the world producing 2.23 Mt. China, Canada and India achieve their large outputs through extensive production of relatively low yielding crops. Average yields for these countries ranged from 1.1 to 1.8 t/ha for the 5-year period 2006-2010. By contrast EU countries generate the largest yields per unit area with 10 countries achieving average yields exceeding 3.0 t/ha over the same period. The UK was ranked eighth in the world with an average yield of 3.3 t/ha compared to 4.0 t/ha for the highest ranked country, the Netherlands.

Oilseed rape yield trends over time for the major producing countries have been analysed recently by Berry and Spink (2006) and Rondanini *et al.* (2012). Rondanini *et al.* reported a linear increase over the period 1970 to 2009 for the majority of countries examined with rates of 15 to 40 kg/ha per year. Two notable exceptions were Chile and the UK. In Chile, no significant improvement was found between 1970 and 1985, but thereafter yields increased at a rate of 98 kg/ha per year. In the UK the opposite trend occurred with an increase of 94 kg/ha per year before 1984, but relatively little improvement since. Rondanini *et al.* (2012) also analysed the seasonal variability of yields and concluded that yield stability has not improved over the last 40 years in any of the countries they studied in spite of the assumed improvements in crop management practice.

Berry and Spink (2006) suggested that for some EU countries, including France and Poland, there was evidence of a slowing down or cessation in yield improvement between 1985 and 2005 similar to that in the UK. Adding yields from 2005 to 2010 (with 2011 data not yet available) indicates that recent trends show improvement in several countries. A number of northern and central European countries display a common pattern of initially declining and then variable yields between the late 1980s and early 2000s followed by a resumption of yield improvement thereafter (Figure 72).

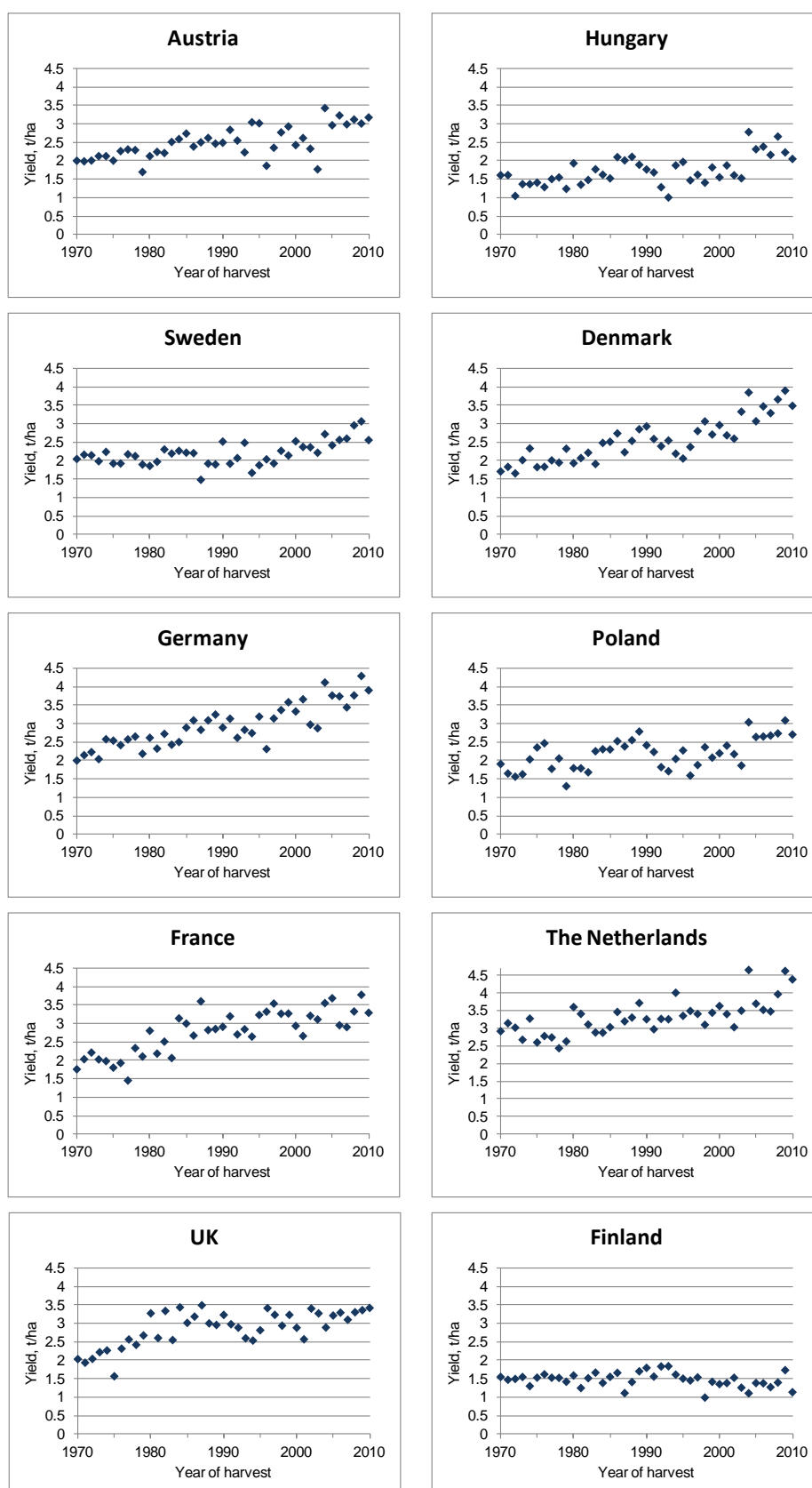


Figure 72. Oilseed rape yield trends for northern and central European countries (source: FAOSTATS 2012).

Even those countries that show an overall linear increase in yield between 1980 and 2010 experienced a period of little or no yield improvement between 1990 and 2000 in common with the UK e.g. Austria, Hungary, Denmark, Poland, The Netherlands and, to a lesser extent, Germany. In Finland from around 1992 onwards, yields have steadily declined. Unfortunately, with the exception of the UK (Booth *et al.* 2005; Berry and Spink, 2006) and Finland (Peltonen-Sainio *et al.*, 2007) there are few published analyses of the factors underlying the yield trends in these countries.

Genetics and yield potential

Benefiting principally from breeding effort in mainland Europe, oilseed rape has evolved through a number of step changes that have, in some cases, slowed or even reversed the rate of yield improvement. The crop has undergone a number of transformations in the quality and nature of its oil. High levels of erucic acid in the diet were thought to pose health risks and during the 1970s varieties were bred that steadily lowered the erucic acid content from around 50% to meet an eventual EU specified maximum of 2%. Rape meal with high glucosinolate content was shown to cause digestive tract problems in non-ruminant livestock and by the early 1980s breeders had made a further breakthrough and were able to achieve glucosinolates of 35 micromoles per gram of seed, compared with the traditional types with levels of about 100 micromoles. The target has recently fallen to 18 micromoles. These two breeding achievements defined the “double low” rape standard that was introduced in 1984. Only crops conforming to this standard were eligible for the crop subsidies then available as part of the Common Agricultural Policy. Both these advances came with a short-term decline in yield in the first varieties to conform to the new standards.

From the early 1990s onwards oilseed rape continued to diversify with the first hybrids appearing in 1993. More recently semi-dwarf hybrids and varieties with further fatty acid modifications have come into production. The semi-dwarf varieties offer excellent resistance to lodging and their short canopy height increases crop management options, including late fertiliser applications. The new fatty acid types have elevated proportions of oleic acid and lowered levels of linolenic acid (HOLL) in their oil, aimed at increasing shelf life and re-use value.

Several authors have highlighted the increase in yields of new varieties in UK trials and have taken this as evidence of improving genetic potential (Sylvester-Bradley *et al.*, 2002; Booth *et al.*, 2006; Berry and Spink, 2006; Spink *et al.*, 2009). Improvements of around 0.033 t/ha and 0.062 t/ha per year have been estimated depending on the period examined (Booth *et al.*, 2006; Berry and Spink, 2006). The period of improvement in variety trial yields coincides with a period of little net yield gain on farm, indicating a widening gap between yield potential and the exploitation of that potential in commercial production. However, it has been noted that the rate of yield improvement in variety trials declined from the late 1990s (Spink *et al.* 2009). From an analysis of yield trends in RL and NL trials, Mackay *et al.* (2010) estimated that, from 1982 to 2007, the improvement in seed yield

attributable to varieties was 0.059 t/ha per year, equal to 94% of the total gain. Improvement in oil content was estimated at 0.092%, 83% of the total gain. Kightley & Horwell (2011) examined trends, from 1984 to 2010, in the yield of new varieties for which an advance was apparent. In their analysis, where only the top yielding varieties were considered, there was no evidence of a slowdown in the rate of improvement in yield potential, of approximately 2% per year.

In Finland the short summer season and harsh winter conditions dictate that spring types of early maturing turnip rape are grown. Swede rape accounts for only about 1-7% of total production (Peltonen-Sainio *et al.*, 2007). As turnip rape is not grown as widely on a global scale as swede rape, the breeding task for this crop falls largely to Finland. Average yields in official variety trials have shown a similar decline to on-farm yields since the early 1990s. However, when the effects of site, year and trial were accounted for statistically as random effects, a steady improvement in yield potential of 17 kg/ha per year was apparent (Peltonen-Sainio *et al.*, 2007).

Climate and weather

About two thirds of the decline in national yields in Finland from the early 1990s has been ascribed to a greater sensitivity of modern varieties to air temperature at flowering and during seed filling (Peltonen-Sainio *et al.*, 2007). Higher mean summer temperatures in recent years and a greater temperature sensitivity of modern varieties was associated with a yield reduction of 55 kg/ha per 1°C increase in temperature. Older varieties by comparison have been shown to have greater yield stability across environments. Temperature sensitivity during critical developmental phases has been reported in other *Brassica* crops including swede rape (Aksouh *et al.*, 2001; Morrison and Stewart 2002; Gan *et al.*, 2004), and varieties can differ in their sensitivity (Gan *et al.*, 2004). However, when swede rape varieties were compared with modern turnip varieties under Finnish conditions, the swede varieties showed an *increase* in yield with increasing temperature (10 kg/ha per 1°C; Peltonen-Sainio *et al.*, 2007). Thus swede rape may have a greater temperature threshold before damaging effects of heat stress occur compared to the modern turnip rape varieties.

Supit *et al.* (2010) conducted an analysis of changes in yield potential caused by shifts in global radiation patterns and temperature from 1976 to 2005. Regional potential yields were predicted using the crop simulation model Crop Growth Monitoring System. Possible limitations due to water availability and differences in variety characteristics were not considered. Predictions suggested no effect of temperature and radiation on oilseed rape yield in the major production areas of England, but a decrease in south west England, Tayside, central and south-east Scotland. In Scotland, this was associated with a decline in incident radiation in spring. Given the relatively small production areas affected, these results would suggest that changing temperature and radiation patterns may not have contributed significantly to the yield trends observed on-farm in the UK.

In common with other crop species oilseed rape is sensitive to restrictions in water availability. However, there is some evidence to suggest that oilseed rape may be more sensitive than wheat, at least for the spring varieties compared directly (Hess, 2012). A positive relationship has been found for yield of winter oilseed rape and June rainfall in commercial crops on a clay soil at ADAS Boxworth in Cambridgeshire, but not on a higher available water capacity (AWC) silty clay loam soil at ADAS Rosemaund in Herefordshire (Blake and Spink, 2005).

Agronomy

Peltonen-Sainio *et al.* (2007) suggested that an increase in disease might also be contributing to the decline seen in the national oilseed rape yield in Finland. Rotations of *Brassica* crops in Finland are narrow, with *Brassica* crops often being sown in the same field every third year instead of the recommended five years. Moreover, fungicides are not commonly used. Although national survey data on disease incidence and severity were not available, there has been an almost exponential increase in the number of sclerotia particles from *Sclerotinia sclerotiorum* found in seed material tested in the Finnish official seed tests since 1999 (Peltonen-Sainio *et al.*, 2007).

In an analysis of UK oilseed rape yield trends from 1987 to 2002, Booth *et al.*, (2005) concluded that disease was an important contributory factor. Reasonable correlations were found between crop yield and the severity of light leaf spot on stems and pods. The effects of disease on annual yield variation were analysed using multiple regression. Of the disease variables examined, only light leaf spot incidence and severity were found to be important. Much of the annual variation in average national yield between 1994 and 1998 was removed when means were adjusted for the effect of light leaf spot. Other contributory factors highlighted were potential sulphur deficiency, the proportion of spring rape grown, and a reduction in N fertiliser application rate (Booth *et al.*, 2005).

Differences in crop management practice adopted in variety trials compared to commercial crops were evaluated by Berry and Spink (2006) and Spink *et al.*, (2009) to identify possible limitations to yield progress in the commercial crop. Several factors were highlighted, including rotation length, cultivations, fungicide and fertiliser use and sowing date. Rotational gaps between *Brassica* crops are typically shorter in commercial production, which can increase soil-borne disease problems. More robust fungicide programmes are used in variety trials than in most commercial crops and trials are typically sown 2-3 weeks later. Early sowing of oilseed rape can result in yield reductions associated with greater pest problems such as cabbage root fly and aphids, viruses and overly dense canopies that are less efficient in their use of light. Other differences highlighted were slower uptake of S fertiliser use on farm and crop establishment techniques. By the early 2000s many farm crops were being established by autocasting directly into the previous cereal crops, direct drilling or drilling after minimum tillage, whereas ploughing was the predominant method used to establish variety trials (Berry and Spink, 2006; Paul Gosling HGCA, personal communication).

3.5.2. Yield trends

National yield trend 1984-2011

This study is focusing on oilseed rape yield trends since the start of the double-low variety era, and therefore the period from 1984 to 2011. Prior to this, trends were heavily influenced by the change from spring to winter sowing and from single to double low varieties. Three phases are evident during this 28 year period (Figure 73). Separate yield data for winter and spring oilseed rape are not available prior to 1999, so combined yields are shown in Figure 73. From 1984 to 1994 yields decreased sharply, from 3.5 to 2.5 t/ha. Between 1994 and 2004 yields fluctuated widely between 2.5 and 3.5 t/ha, but since 2004 yields have increased steadily from 3.0 t/ha to nearly 4.0 t/ha in 2011. Fitting a second degree polynomial trendline to the yield data, and taking the average slope for each of the three phases, the yield decline from 1984 to 1994 was equivalent to -0.040 t/ha per year. Between 1994 and 2004 there was only minimal yield improvement equivalent to 0.022 t/ha per year, but since 2004 the yield trend shows an average increase of 0.075 t/ha per year.

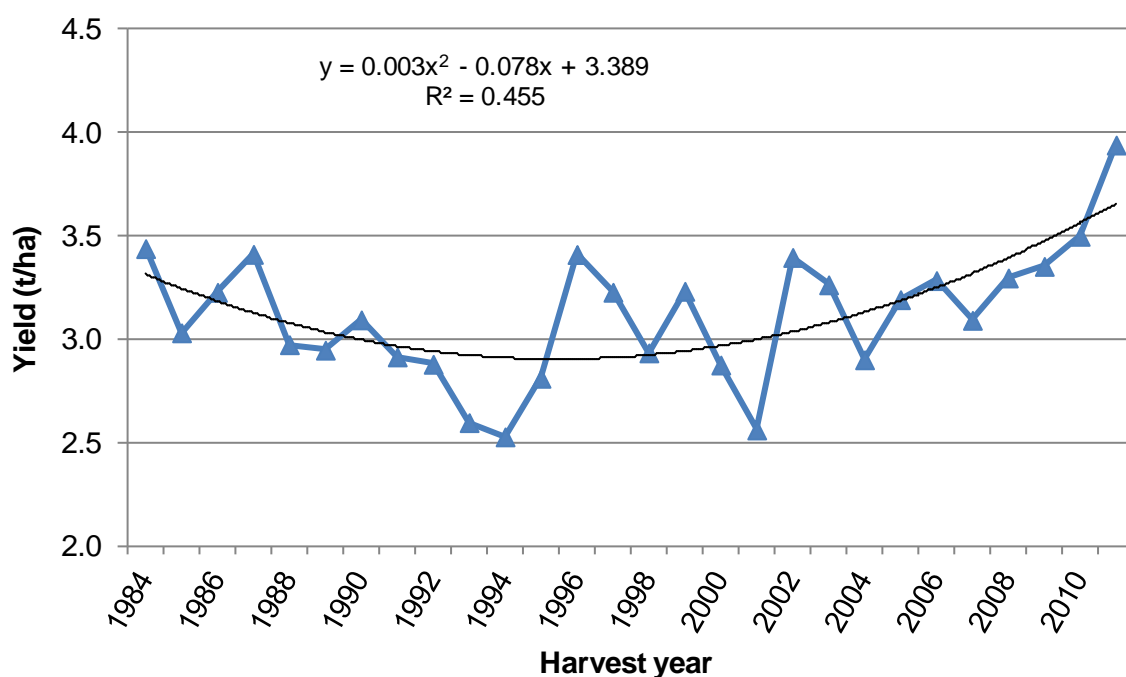


Figure 73. UK national average oilseed rape yield trend in the double-low era from 1984 to 2011 ($x = 1$ for 1984).

Regional yield trends

Data are available separately since 1999 for the four home countries and eight English regions. A comparison of UK mean yields with those of the home countries is given in Figure 74. The vast majority of the UK oilseed rape crop, 94.6%, is grown in England and the similarity between the yield patterns for the UK and England is to be expected. The similarity with the combined Wales and Northern Ireland picture is perhaps more surprising, given the generally wetter climate in those

areas. In Scotland the rate of yield increase had been showing signs of slowing prior to 2011, although the crop had been higher yielding than the UK average for much of the period.

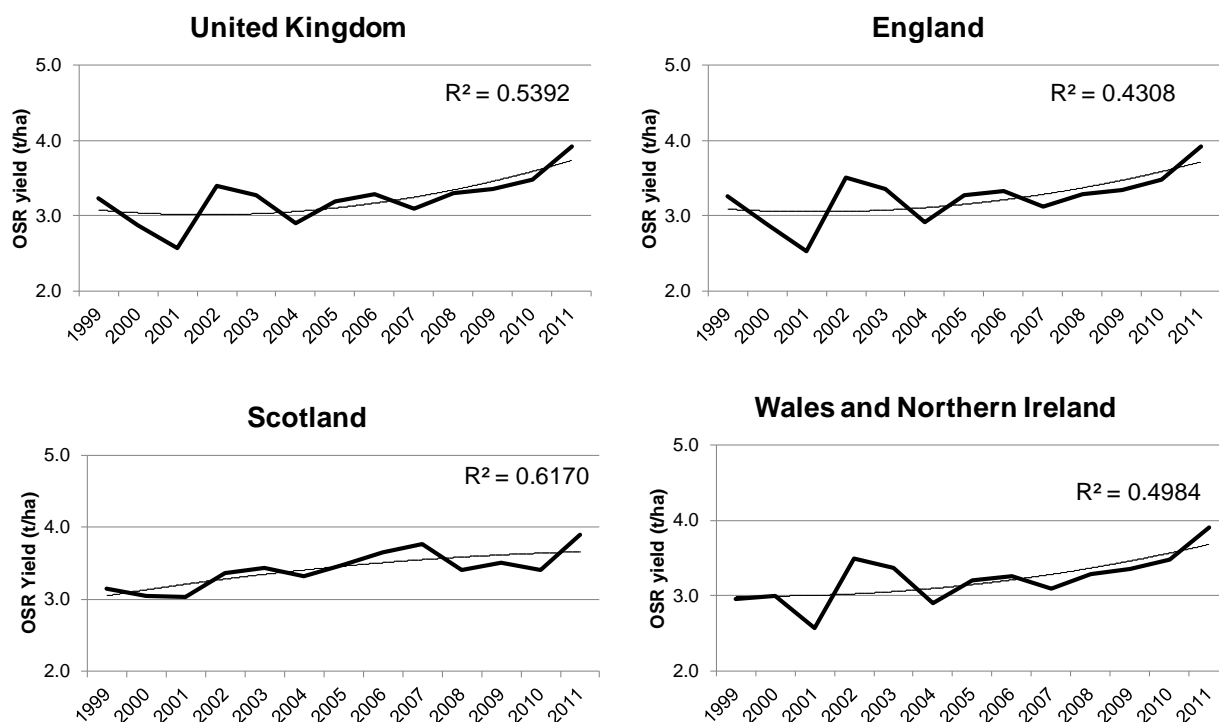


Figure 74. Oilseed rape yield trends for UK, England, Scotland, Wales and Northern Ireland 1999 - 2011.

Looking at the English sub-regions, there is some variability in their oilseed rape yield trends, in particular the high yielding years of 2002 – 2003 and the record yielding year of 2011 (Figure 75). However, an increasing yield trend is observed for all eight regions.

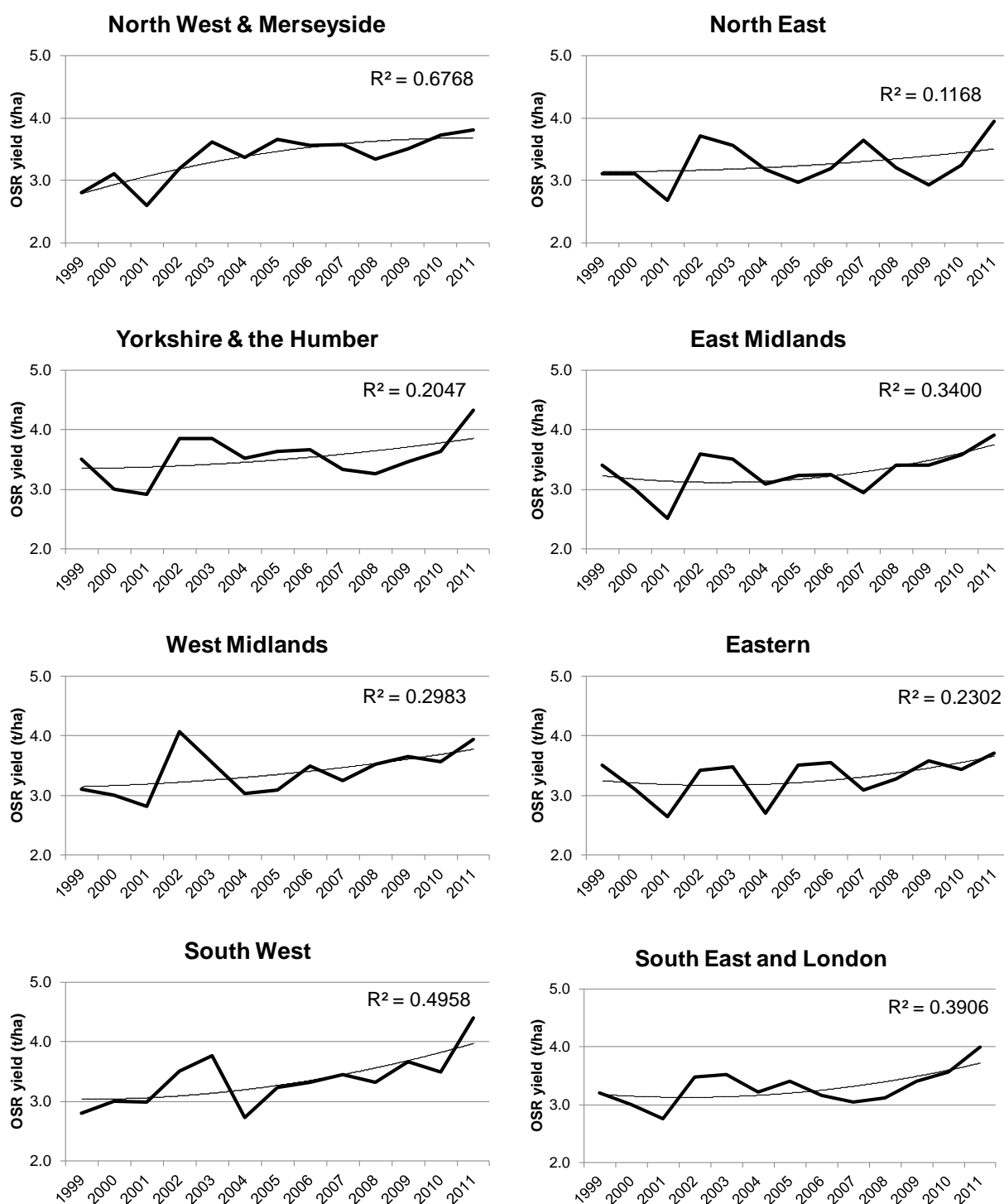


Figure 75. Oilseed rape yield trends for English sub-regions 1999 - 2011.

The impact of spring oilseed rape

Oilseed rape is complicated by the inclusion of the lower-yielding spring oilseed rape crop within the UK yield data set. Spring oilseed rape has been presented separately in Defra statistics since 1999, but only for England, and it is known to have contributed significantly to the national crop in the 1970s and 1990s. Figure 76 shows the proportion of the English crop sown with spring oilseed rape from 1999 to 2011, together with yields for the English spring and winter sown crops.

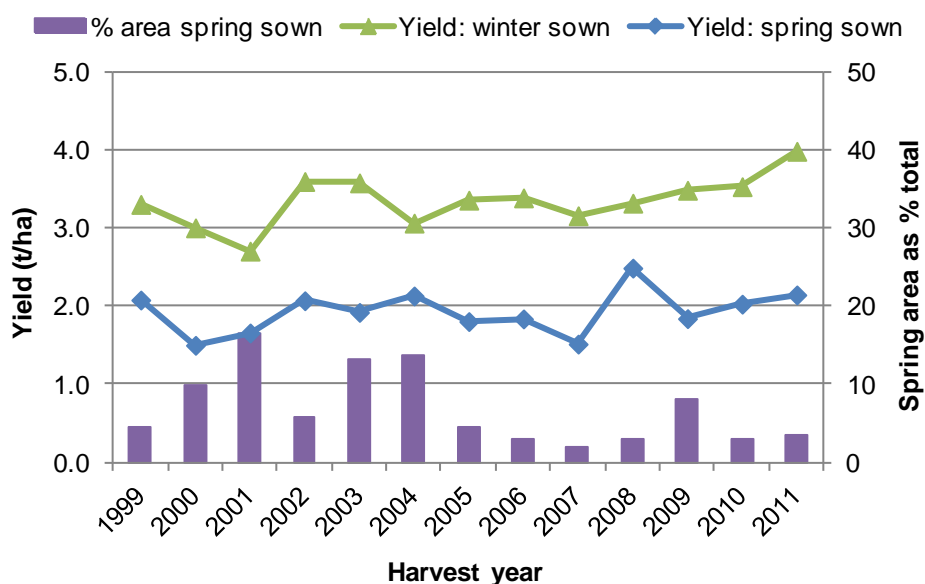


Figure 76. Proportion of the English oilseed rape area sown in spring and comparison of winter and spring oilseed rape yields.

Inspection of the separate yield lines reveals no consistent relationship between annual winter and spring oilseed rape yields. This is to be expected, as the two crops will be subject to very different combinations of weather for their establishment, growth and maturation phases. Table 17 shows the combined average winter plus spring oilseed rape yield as a percentage of the winter oilseed rape yield, based on Defra statistics for England from 1999 to 2011. The impact of the area sown with spring oilseed rape is evident, with yield depressions of over 6% observed in 2001 and 2003.

Table 17. Impact of spring oilseed rape inclusion on oilseed rape yield estimates for England.

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Average yield of winter plus spring oilseed rape as a % of winter only	98.7	96.1	93.6	97.5	93.9	95.4	97.6	98.4	98.9	99.2	96.2	98.8	98.4
% of crop area sown with spring oilseed rape	5	10	17	6	13	14	5	3	2	3	8	3	3

It is clear that the area of spring sown oilseed rape has had an important influence on year-to-year variation in the national average oilseed rape yield. It is therefore essential that an estimate is made of the impact of changes in the spring oilseed rape area over the period from 1984 to 2011. A further measure of this is provided by seed certification statistics. Figure 77 shows the % of the total oilseed rape certified seed area and final seed weights accounted for by spring oilseed rape varieties, data for which are available for the UK from 1984 to 2011. The peak in the proportion of spring oilseed rape seed production coincides with the introduction of the Arable Area Payment Scheme, when spring oilseed rape enjoyed a period of popularity due to its lower input costs.

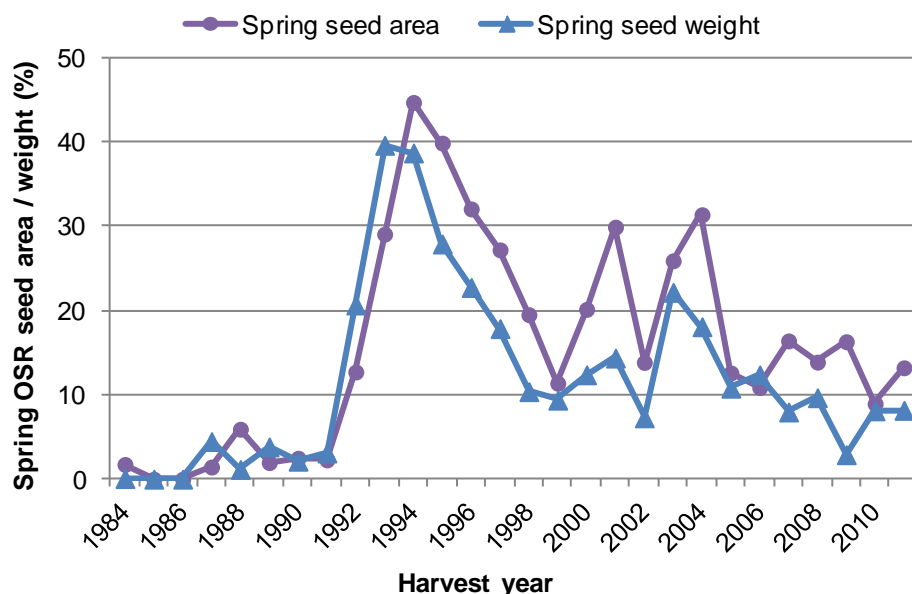


Figure 77. Variation in the proportion of the oilseed rape certified seed area and final seed weights accounted for by spring oilseed rape varieties from 1984 to 2011.

Comparison of the % of the certified seed area sown with spring varieties and the % of the farm crop area sown with spring varieties from 1999 to 2011 showed a close relationship ($\% \text{ spring crop area} = 0.44 \times \% \text{ spring seed area}$, $R^2 = 0.77$, $SE = 0.035$, $P < 0.001$). Although it is not possible to determine a precise picture of the farm spring oilseed rape area due to a lack of direct information and the unknown effects of imported and farm-saved seed, this further measure appears to give a useful estimate. This relationship was therefore used to estimate the % of the farm crop area sown with spring varieties for the entire period from 1984 to 2011. Charting estimated % spring oilseed rape area against UK average yields confirms this as an important influence over time (Figure 78).

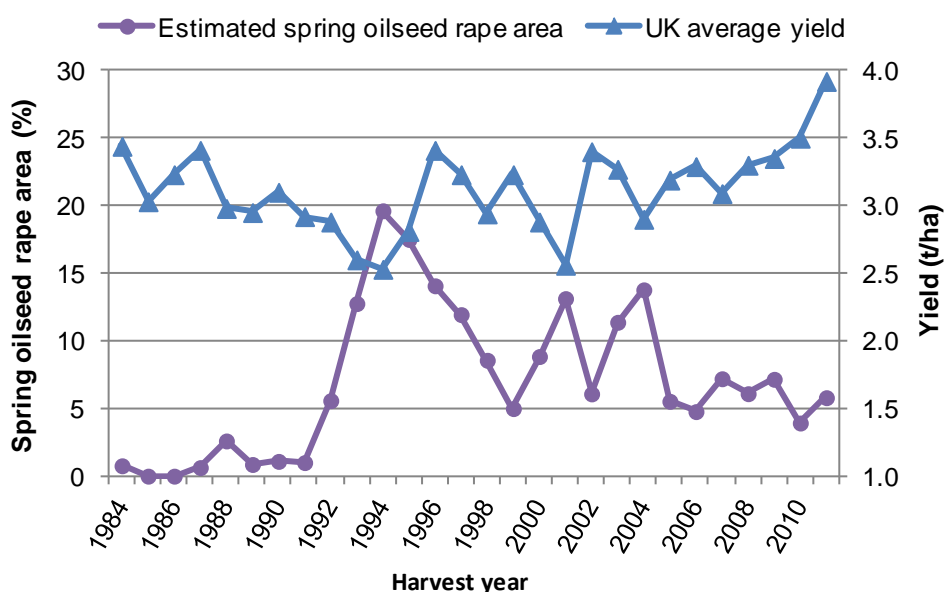


Figure 78. Variation in the estimated proportion of the oilseed rape crop area sown with spring varieties compared to UK average oilseed rape yields from 1984 to 2011.

Mean yields from official variety trials were used to estimate spring oilseed rape yields as a proportion of winter oilseed rape yields each year (average 59%, range 47-68%). Using these two sets of values an estimate of the reduction in the national average yield due to the area of spring oilseed rape grown (compared to 100% sown with winter oilseed rape) was calculated (Figure 79). A check between these estimates of lost yield and those from Defra statistics from 1999 to 2011 showed good agreement in 10 out of 13 years, but with a slight tendency to underestimate the reduction in yield (Defra values = 1.16 x estimated values, $R^2 = 0.52$, SE = 0.33, P = 0.005). Based on the annual yield reductions indicated in Figure 79, it is estimated that from 1984 to 1994 the average loss of yield improvement due to the overall increase in the spring oilseed rape area was equivalent to about 0.009 t/ha per year. Between 1994 and 2004 there was considerable year to year variation, with little overall trend. Since 2004 the reduction in spring oilseed rape area has resulted in a positive contribution to yield improvement equivalent to about 0.008 t/ha per year.

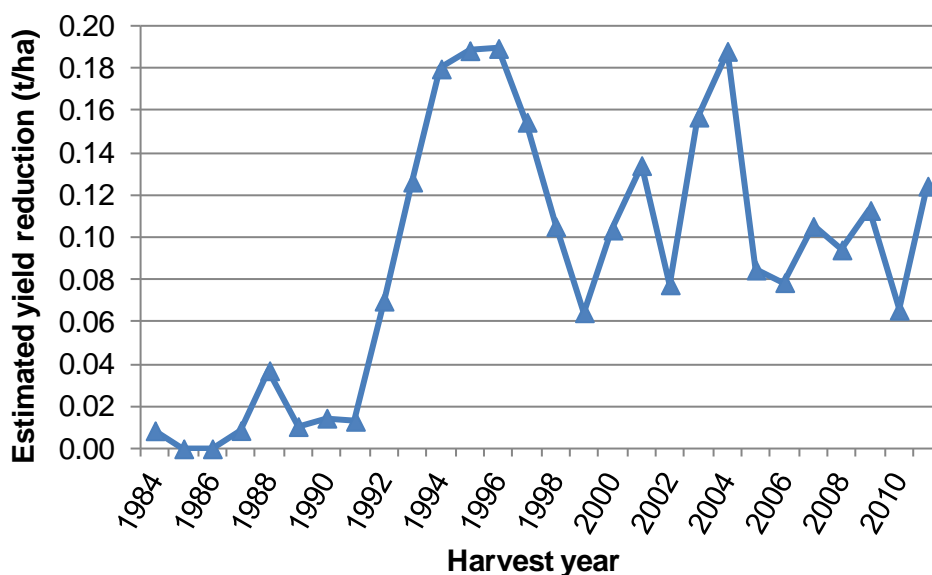


Figure 79. Estimated reduction in national yield (compared to 100% winter oilseed rape) due to area of spring oilseed rape grown between 1984 and 2011.

Differences between farms

Further insight into oilseed rape yield trends is provided by Farm Business Survey data, based on approximately 400 samples per year for the period from 1987 to 2009. Dividing the data into four yield quartiles (Figure 80) indicates that there are no obvious differences in yield trend between the yield quartiles. Bearing in mind the impact of spring oilseed rape on national yields, the bottom quartile yield may be particularly influenced by spring cropping. Because of this, in the chart below (Figure 81) the yield gap trend between the top quartile and each of the successive quartiles is presented. After a period of growing differential in the 1990s there is no indication of further divergence.

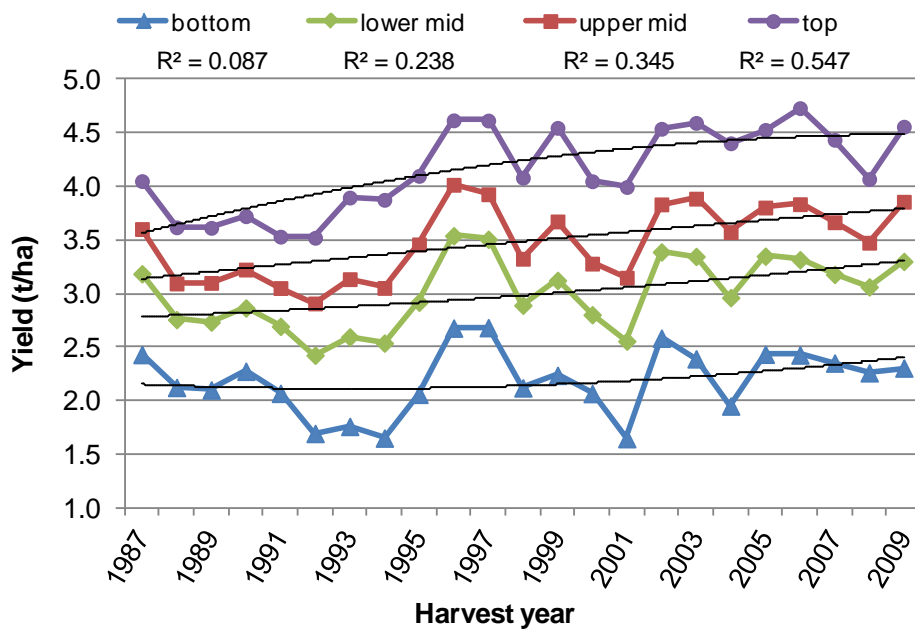


Figure 80. Oilseed rape yield trends within Farm Business Survey yield quartiles.

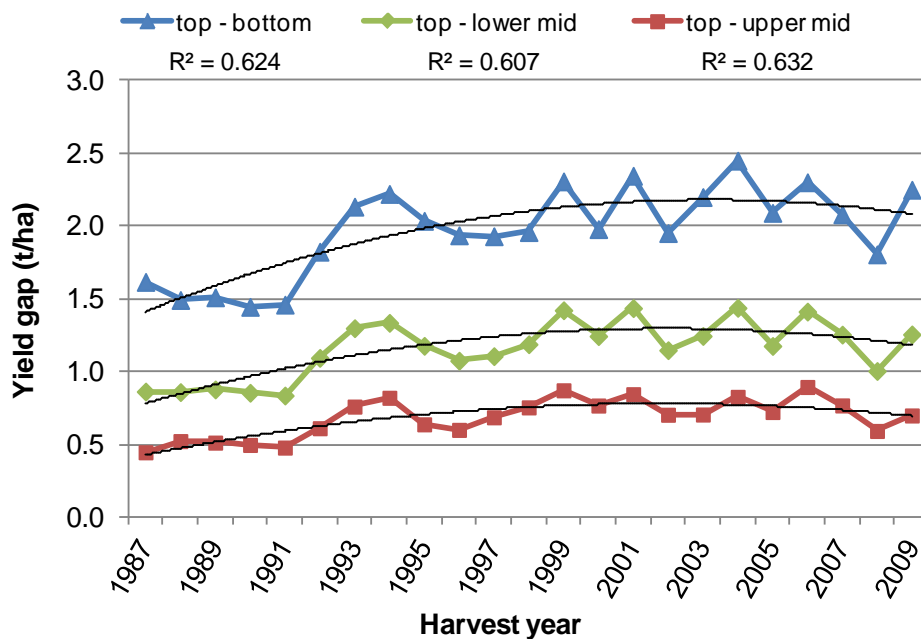


Figure 81. Annual yield gap between FBS top, middle and bottom oilseed rape yield quartiles.

Dividing the data by oilseed rape gross margin instead, it is evident that farms in the top quartile for gross margin for the period from 2004 to 2009 have also achieved the highest mean yield, and farms in the bottom quartile for gross margin have achieved the lowest yield (Figure 82). However, the yield gap between farms in the top and bottom gross margin quartiles is not increasing.

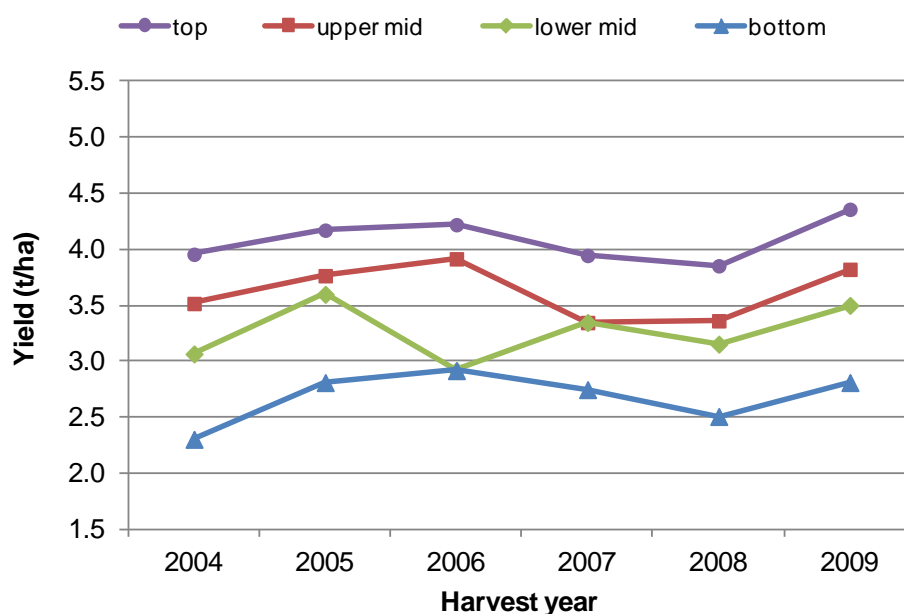


Figure 82. Recent oilseed rape yield trends within FBS gross margin quartiles.

No consistent relationship is evident between yield quartile and oilseed rape crop area in the Farm Business Survey data from 2004 to 2009. There has been a tendency for the top yield quartile to have grown the largest oilseed rape crop area and the bottom quartile the smallest area, but the magnitude of this difference has varied from year to year (Figure 83). This is partly due to greater year-to-year variation in the area of oilseed rape grown by farms in the top yield quartile.

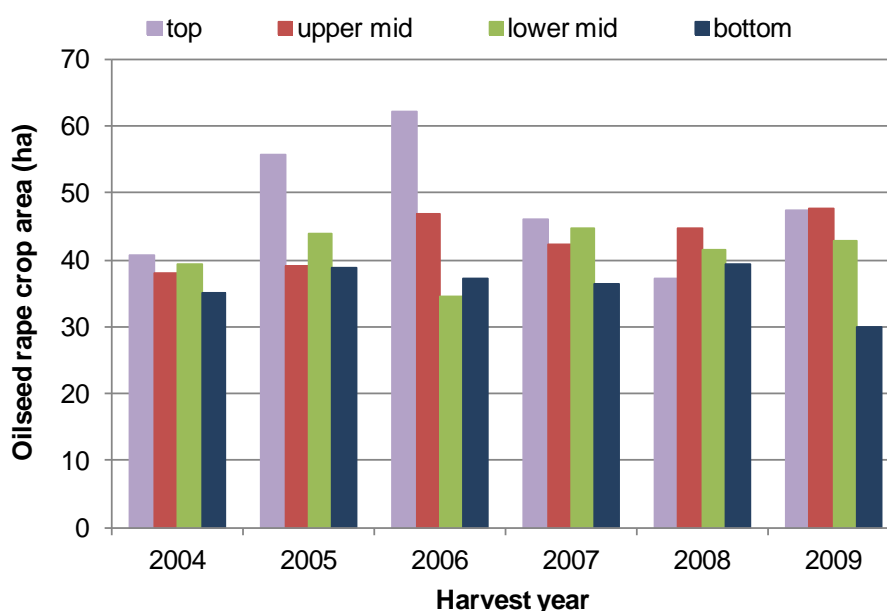


Figure 83. Mean area of oilseed rape grown by each FBS yield quartile.

Most of the case study farms that were examined show a rising farm average oilseed rape yield trend since the early to mid-2000s (Figure 84). On some farms the rate of increase has been dramatic e.g. Lincolnshire 1, Dorset 1. On other farms yields are not increasing e.g. Norfolk 3, but in the latter case the farm has always produced yields that are above the national average.

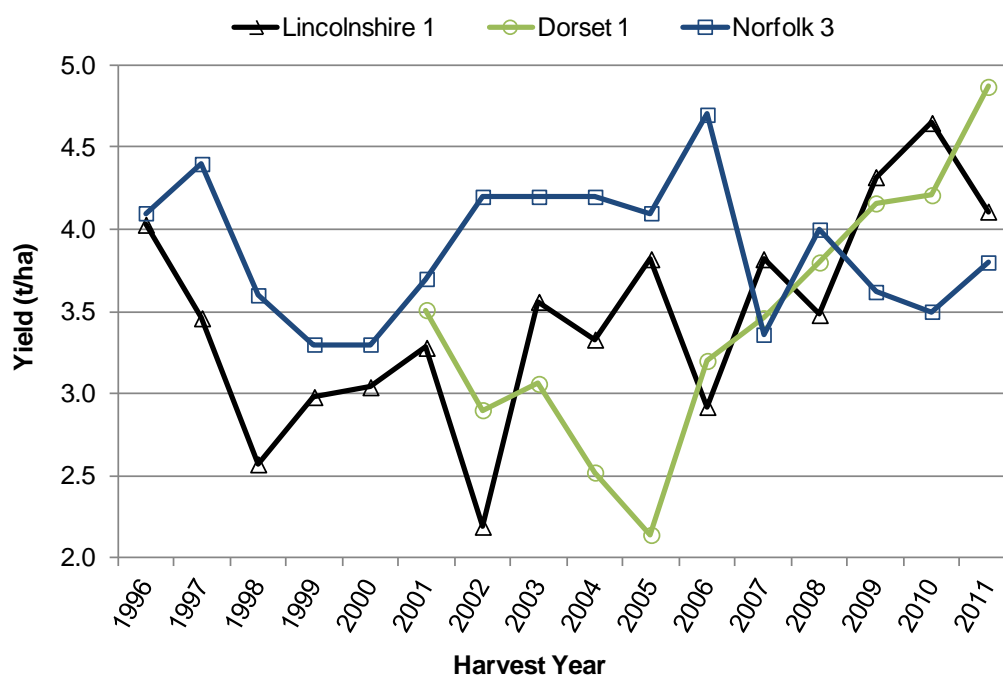


Figure 84. Recent winter oilseed rape average yield trends for three case study farms in England.

Key features of the three case study farms illustrated in Figure 84 are as follows:

Lincolnshire 1 (farm size c. 430ha, mainly shallow soil and growing 30-80ha of oilseed rape):

- Most if not all of the crop having a break of 3 or more years between oilseed rape crops;
- Most if not all of the crop following barley in the rotation;
- 100% ploughed and straw removed until 2009, with move to 50% or more 'subcasting' since;
- Above-average N fertiliser use (230 kg N/ha in total);
- 100% of the crop receiving P, K and (since 1999) S fertiliser.

Dorset 1 (farm size c. 500ha, medium soil and growing 30-80ha of oilseed rape):

- Most if not all of the crop having a break of 3 or more years between oilseed rape crops;
- Range of preceding crops (but mostly cereals);
- 100% shallow non-inversion since 2003 (some ploughing or direct-drilling before that);
- Average N fertiliser use (180-200 kg N/ha) but all crop has received organic manure since 2003;
- 100% of the crop receiving S fertiliser since 2003.

Norfolk 3 (farm size c. 230ha, medium and deep clay soils and growing 30-60ha of oilseed rape):

- All of the crop having a break of 3 years between oilseed rape crops;
- About half of the crop following wheat, and half following barley;

- A mix of ploughing and deep non-inversion establishment since 1996;
- Average N fertiliser use (180-200 kg N/ha) but all crop has received organic manure since 1996;
- 100% of the crop receiving S fertiliser since 2000.

Overall examination of all of the case study farms does not highlight any specific single agronomic factors that may be associated with high / increasing or low / decreasing oilseed rape yields. A range of establishment, rotational and crop nutrition practices appear capable of delivering above average or rising farm yield trends. However, it is notable that all three of the above case study farms have maintained a break or mainly 3 or more years between oilseed rape crops.

3.5.3. Genetics and yield potential

Using a combination of NL and RL data Kightley and Horwell (2011) examined yield improvement in oilseed rape. Their analysis showed that, after a 10% yield drop associated with the introduction of the first 'double-lows', new varieties have offered a consistent yield advance of about 2% per year, compared to the yield of the first double low variety in 1984. The analysis has been updated to incorporate additional data from the high yielding 2011 harvest (Figure 85). The chart shows linear trend lines for the three discreet breeding types: conventional 'open pollinated' varieties, hybrids and recently-introduced semi-dwarf hybrids. The markers are for varieties that represented yield progression and indicate and their 'lifetime' average yields (Appendix Table 3) with comparisons based on a two-stage fitted constant analysis. The estimated annual yield increases for the three groups are 0.06 t/ha for conventional varieties, 0.05 t/ha for hybrids and 0.07 t/ha for semi-dwarf hybrids. These are comparable with previous estimates, and equate to a potential average yield gain on farm of 0.048 t/ha per year.

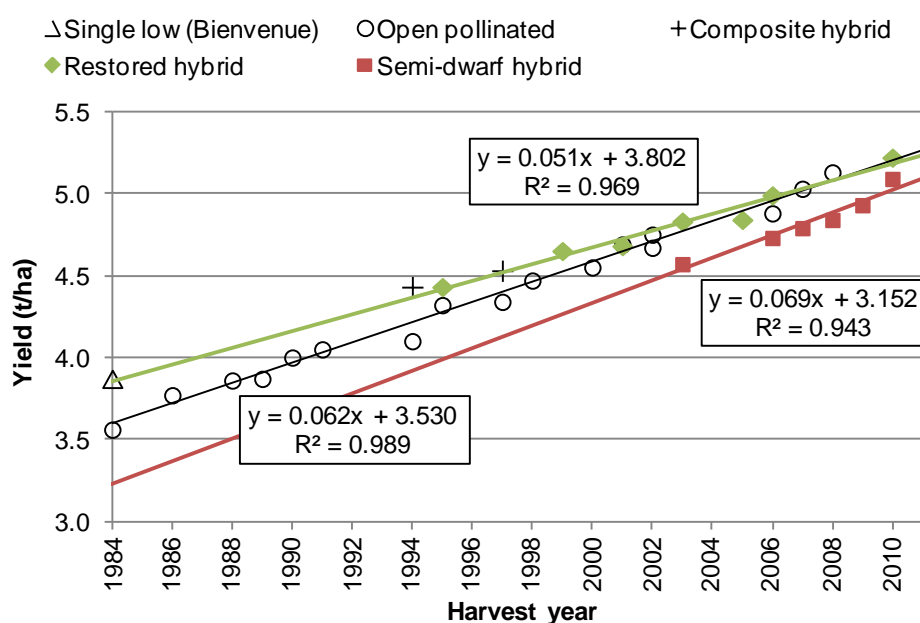


Figure 85. Variety improvement in winter oilseed rape 1984 - 2010.

It is clear from certification statistics, even allowing for the absence of hybrids, that the oilseed rape seed market is very fragmented, considering its small range of end use specifications. The top 15 varieties in terms of their contribution to final seed weights certified in the years 1990-2011 have been documented (Appendix Table 4). This amounts to some 138 varieties, with the vast majority designated for the double-low market and just a minority for the specialist high erucic acid market. It compares with just 64 wheat varieties, competing in four nabim groups over the same period. Relatively few varieties have achieved enduring popularity. This reflects a number of issues:

1. Oilseed rape is a very difficult crop to trial and performance from site to site and year to year can be very variable. As evidenced in Appendix 3 there are numerous cases of varieties being commercialised briefly, on the basis of very good yields in early years, but subsequently achieving lower yields, or demonstrating unfavourable agronomic characteristics. Some of these varieties have achieved significant market shares before rapidly losing popularity. This was particularly evident in the initial phase of the double low era when, in order to 'fast track' new varieties to meet the needs of growers, varieties were considered for Recommendation after only two years of trials. Once an adequate flow of double low varieties had been established Recommendation was moved to the end of Year 3 which addressed this problem to a large extent and the assignment of new varieties to a provisional 'P' category warns growers to be cautious in the uptake of these varieties as their performance level continues to settle down.
2. The nature of the oilseed rape crop means that the varieties that do achieve long-term market success are usually those that combine an advance in yield with good agronomic characters, especially short plant height combined with good standing ability. Over the 20-year period this has been illustrated by varieties such as Capricorn, Apex, Canberra, Castille and Es Astrid. All these maintained significant market shares after their yields had been superseded. To an extent the emphasis on short crops with good lodging resistance has diminished, due to the introduction of fungicides with growth regulatory effects and a better understanding of optimum seed rates. In recent years, stimulated by high crop prices, growers have shown more willingness to grow taller and weaker varieties if they offer high yields, given the management tools at their disposal.
3. Some varieties achieve limited success without any independent UK trials data. These are Common Catalogue varieties, which have been registered in other EU states and have been marketed directly on the basis of information supplied by distributor companies.
4. Finally there are specialist types grown for their specific oil characteristics. These include high erucic acid (HEAR) varieties, produced for industrial markets, and high oleic / low linolenic (HOLL) varieties, characterised by the fatty acid status of their oil composition. Both have been subject to

less intensive breeding effort than standard double lows and are relatively low yielding. Growers of these are incentivised by contract price premiums to compensate for reduced yield potential but they inevitably dilute overall farm yield averages. Within these categories there are varieties that have been fully tested within the UK, but there are also varieties for which independent data is not available. Though there are detailed records of varieties undergoing seed certification, uptake of new varieties is less easy to quantify than for wheat because of the high proportion of farm saved seed and the growing of hybrids, the seed for which is mostly imported and not recorded.

An assessment of the impact of variety selection on the national yield trend, and comparison with the yield that could have been achieved by growing the highest yielding variety, is presented in Figure 86. The 'best variety' line represents the theoretical yield that would have been achieved had the highest yielding variety available to that date been grown exclusively (based on the lifetime average yields of those varieties). In practice of course that would not be possible or desirable due to the associated agronomic implications and risks. The slope is consistent with that shown for genetic improvement for the 1984 to 2011 period in Figure 85. The 'variety sets' yield line is based on the variety composition from annual seed production statistics and the lifetime mean yields of those varieties. The chart suggests that until 2004 there was a growing divergence between yield potential based on the best variety and yield potential of the variety set grown. The average gap in the yield trends has exceeded 0.5 t/ha since the late 1990s, but from 2004 onwards the two trends have been running more or less in parallel with an average gap of about 0.75 t/ha (Figure 87).

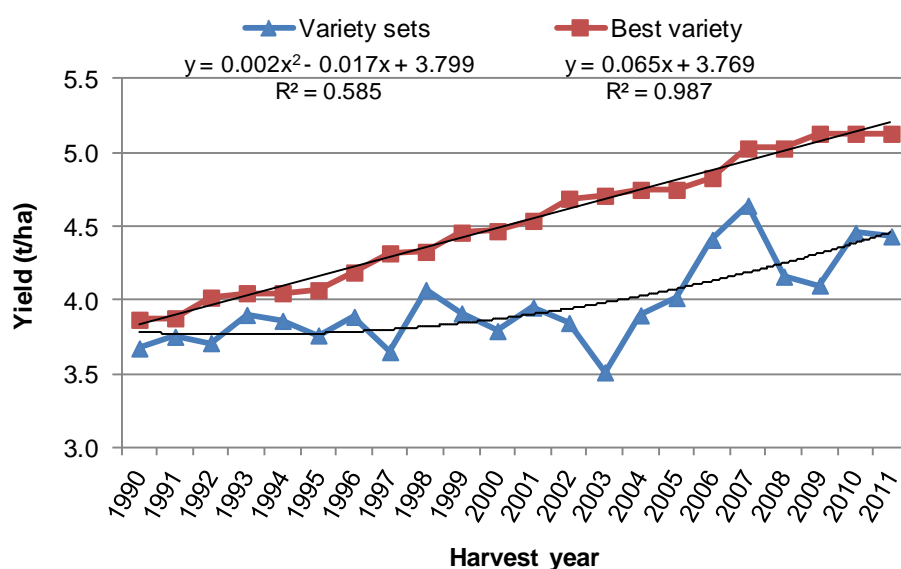


Figure 86. Projected yield trends based on the best available varieties and variety set with composition based on annual seed production statistics ($x = 1$ for 1990).

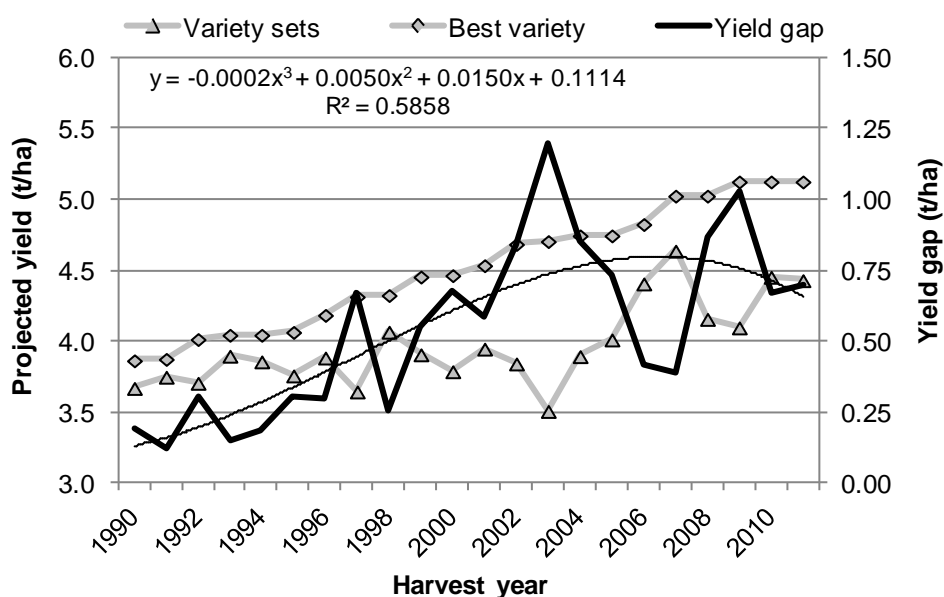


Figure 87. Gap between projected yields based on the best available varieties and variety set with composition based on annual seed production statistics ($x = 1$ for 1990).

Seed certification statistics are an accurate data source but cannot entirely reflect variety choice. Some seed will not be sold and variable proportions of the crop area will be sown with farm saved seed and imported hybrid and conventional seed. Farm saved seed will broadly reflect the previous year's conventional variety sales. While the hybrid Excalibur has achieved considerable popularity there has to date been little evidence of other hybrid varieties achieving a significant market share. Therefore, while this cannot be quantified with certainty, it is estimated that poor uptake of the highest-yielding new varieties reduced the on-farm yield gain due to genetic improvement by more than half between 1984 and 2004. Estimated average reductions in yield improvement (based on Figure 87) are up to 0.031 t/ha per year from 1984 to 1994, and 0.038 t/ha per year from 1994 to 2004. Since then, much better uptake of new varieties has led to a slight closing of the yield gap, with a small overall positive contribution to yield improvement, estimated at 0.014 t/ha per year.

Three recent independent surveys shed some light on growers' preferences. They include a NIAB TAG survey of oilseed rape agronomic practices from harvest 2010, and HGCA planting surveys from autumn 2010 and 2011 (Table 18). Of the varieties listed with 5% or more representation in the surveys, only one (Excalibur) is a hybrid. The current leading hybrid, PR46W21, does not feature. The enduring popularity of the short, conventional variety, Castille, is evident. Calculating the potential yield of the 6 varieties representing 64% of the HGCA 2011 planting survey predicts 4.9 t/ha, or 95.7% of the yield of current top variety, Sesame, based on trial yields. This will over estimate farm yields by about 20% as trial yields exceed farm yields by approximately this amount. This suggests improved uptake of high yielding varieties in the current season. However there is a high proportion of additional varieties at less than 5% of the returns in all three surveys.

Table 18. Summarised variety choice survey data. *Others are recorded at less than 5% of the total.

AHDB HGCA planting area surveys				NIAB TAG variety choice survey	
2011		2010		2010	
DK Cabernet	24	Castille	20	DK Cabernet	31
Excalibur	12	DK Cabernet	16	Castille	20
Castille	9	Excalibur	11	Excalibur	8
Catana	7	Catana	8		
Vision	7				
Sesame	5				
Others*	36	Others*	45	Others*	41 (32 cvs)

Data from the Farm Business Survey reveal no notable differences in average farm expenditure on oilseed rape seed between any of the yield quartiles, with all of them showing a slight upward trend in the last few years.

3.5.4. Climate and weather

The evaluation of possible climate or weather impacts on yields from 1984 to 2011 included:

1. An examination of seasonal weather trends for the UK as a whole, to highlight the key changes over time (see section 3.3.5);
2. An analysis of correlations between de-trended UK yields and individual monthly mean weather variables for the UK and separately for England, in order to identify weather variables that may be associated with annual yield variation;
3. A comparison of trends in specific monthly mean weather variables for UK or England with the UK yield trend;
4. A multivariate analysis to look at the combination of weather factors that may be important.

Monthly mean weather variables

Correlations between de-trended UK oilseed rape yields (combined winter and spring) and individual UK monthly mean weather variables were examined for the 'harvest' years from 1984 to 2011 (Table 19). Each harvest year ends in July and includes August to December of the previous year. As the majority of the oilseed rape crop is grown in England, UK yield correlations with monthly mean weather variables for England have also been examined for the same period (Table 20). Monthly data for the UK or for England have been used to illustrate trends in specific weather variables from 1984 to 2011 in Figures 89 to 92.

Table 19. UK average oilseed rape yield correlations with UK weather from 1984 to 2011.

UK	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL
Rainfall	0.030	-0.147	0.058	-0.080	-0.399	-0.219	0.021	-0.274	-0.545	0.219	0.050	-0.041
Sunshine	0.008	0.013	0.061	0.167	0.199	-0.198	-0.109	-0.042	0.430	-0.105	0.056	0.096
Mean Temp	-0.007	-0.095	0.449	-0.111	-0.364	-0.324	-0.173	-0.213	0.276	-0.283	-0.079	-0.045
Max Temp	-0.020	-0.120	0.473	-0.110	-0.330	-0.360	-0.162	-0.171	0.380	-0.299	-0.035	0.024
Min Temp	-0.017	-0.081	0.412	-0.120	-0.386	-0.274	-0.169	-0.251	0.056	-0.226	-0.172	-0.178
Significance Levels		5% 5%	+ve -ve	0.374 -0.374		1% 1%	+ve -ve	0.479 -0.479				

Table 20. UK average oilseed rape yield correlations with weather for England from 1984 to 2011.

England	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL
Rainfall	0.232	-0.110	-0.078	0.200	-0.229	0.009	-0.052	-0.088	-0.421	0.156	0.031	0.400
Sunshine	-0.361	0.137	0.028	0.183	0.448	0.130	-0.172	0.318	0.514	-0.001	0.272	-0.163
Mean Temp	-0.062	0.291	0.194	0.094	-0.367	-0.120	-0.049	-0.132	0.482	0.125	0.302	-0.036
Max Temp	-0.151	0.269	0.234	0.085	-0.311	-0.127	-0.067	-0.014	0.548	0.086	0.318	-0.059
Min Temp	0.105	0.269	0.149	0.093	-0.393	-0.118	-0.036	-0.274	0.297	0.169	0.216	0.020
Significance Levels		5% 5%	+ve -ve	0.374 -0.374		1% 1%	+ve -ve	0.479 -0.479				

National oilseed rape yields and UK temperatures for October show a positive correlation. This could be due to better early autumn plant and root growth, although no such relationship is evident for September or November so this should be treated with caution. Figure 88 charts UK yields against average maximum October temperatures for England. There is considerable similarity between the patterns of annual variation for yield and temperature, until the last four years.

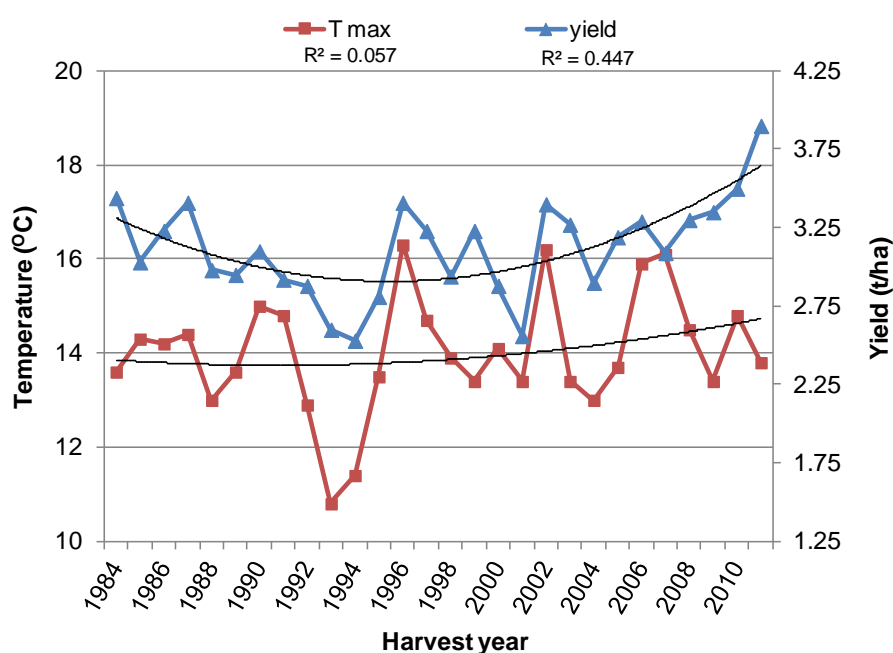


Figure 88. Trends for UK average oilseed rape yield and UK October maximum temperature.

Favourable December conditions are characterised by low rainfall and cold weather (Tables 19 and 20). These are likely to suppress the effects of some pests and diseases, including phoma but not light leaf spot. Figure 89 charts UK yield and December minimum temperature for England.

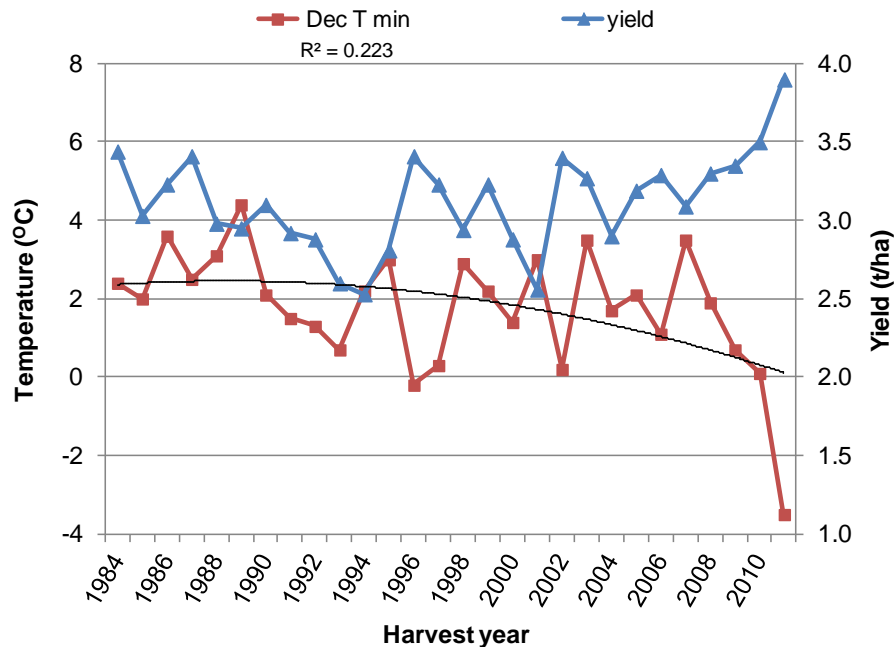


Figure 89. Trends for UK oilseed rape yield and December minimum temperature for England.

April is observed as the critical month of the main growing season, with a significant (1%) negative interaction with rainfall and positive correlations with sunshine hours and maximum temperature for England. Figure 90 charts sunshine and rainfall for England against UK yield for 1984 to 2011. The similarity between the yield and April sunshine trends is particularly striking, with evidence of a positive relationship between yield and sunshine hours (Figure 91).

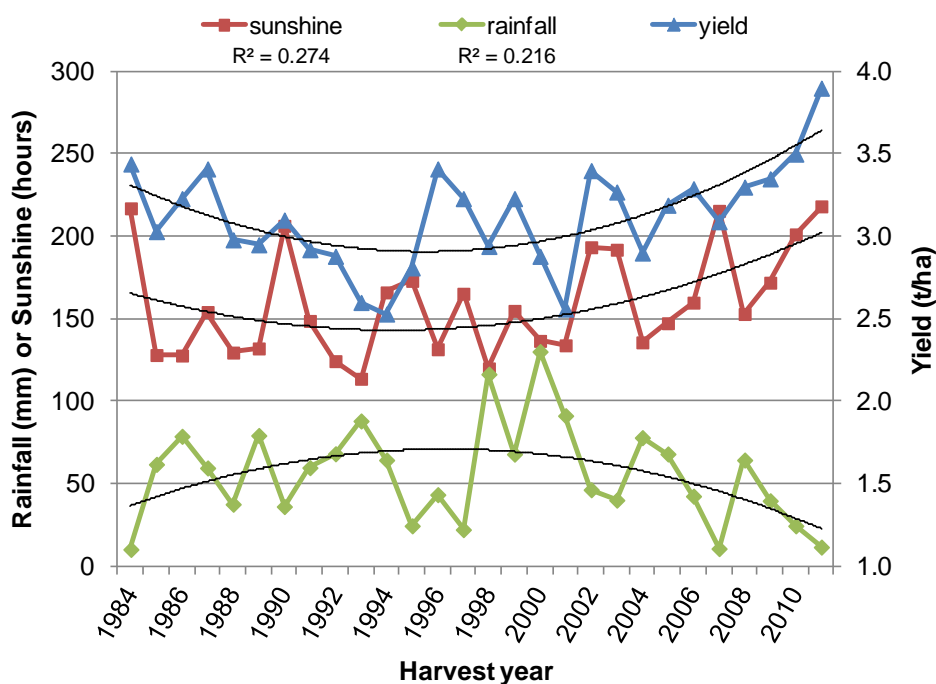


Figure 90. Trends for UK average oilseed rape yield and April rainfall and sunshine for England.

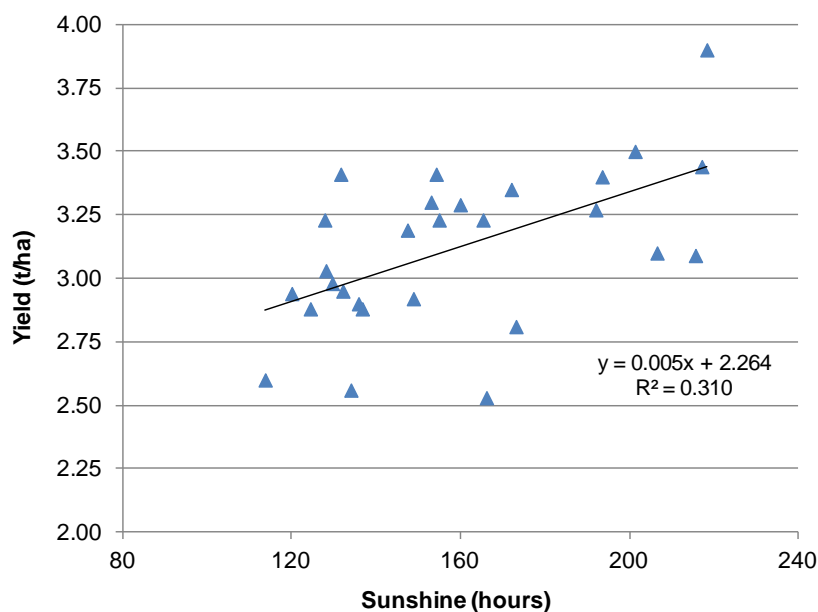


Figure 91. Relationship between UK average oilseed rape yield and April sunshine hours for England ($P = 0.0021$; SE slope 0.0016, intercept 0.2552).

Two interpretations of the response to dry, sunny April conditions have been put forward. Firstly, these conditions can delay the uptake of spring N fertiliser, with the effect of reducing canopy size but optimising N supply for the seed development phase. Reducing crop growth and the thickness of the flower layer will also reduce light reflection and increase photosynthesis. Secondly, they are most favourable for pollination and seed set. It has been shown that oilseed rape yields are increased by up to 30% by cross-pollination, with insect pollination contributing up to a 15% yield increase even if unfavourable wind conditions lead to minimal abiotic pollination (European Crop

Protection Association, 2011). Seed set has also been shown to be positively related to the amount of crop photosynthesis from mid-flowering onwards (Mendham *et al.*, 1981; Leterme, 1988). A negative yield relationship with rainfall during flowering and positive relationship with radiation sum have recently been observed in Germany in experiments conducted over the 1992-2011 period (Weymann *et al.*, 2012).

The apparent lack of a positive interaction with rainfall at any point in the year is perhaps surprising but may support popular theories that very lush oilseed rape crops often fail to produce high yields because of over-thick canopies. Lack of conspicuous rainfall dependency in autumn might also be explained. While both drought conditions and excessive rainfall, with associated slug infestations, might lead to crop failure, this will often go unregistered in national statistics, as the land might be re-planted with another crop.

Multivariate analysis of weather data

Multivariate analysis was completed following the same processes as used for wheat and the results were similar. The initial analyses suggested the combination of weather patterns in the single variate correlations play an important role in the resulting oilseed yield (see Appendix Table 8) but there appears to be over-fitting of the model to the data. The data was subsequently analysed using both Ridge and Lasso regressions and also analysed using Principal Component Analysis (PCA). For all the analyses, once year is taken out, no obvious patterns in the weather data can be identified.

3.5.5. Economics and policies

Policy factors that may have had an influence on national oilseed rape yield trends are outlined in section 3.4.6. Economic factors are outlined below.

Market Prices

Figure 92 shows the yield data for oilseed rape against market prices, unadjusted for inflation. After a period of price protection, oilseed rape prices fell sharply after 1991, and remained relatively low until rising rapidly from 2006 to 2011. Clearly, the prices and yields follow different overall trend shapes but there may be some lag effect in which price signals are leading to changes in yield.

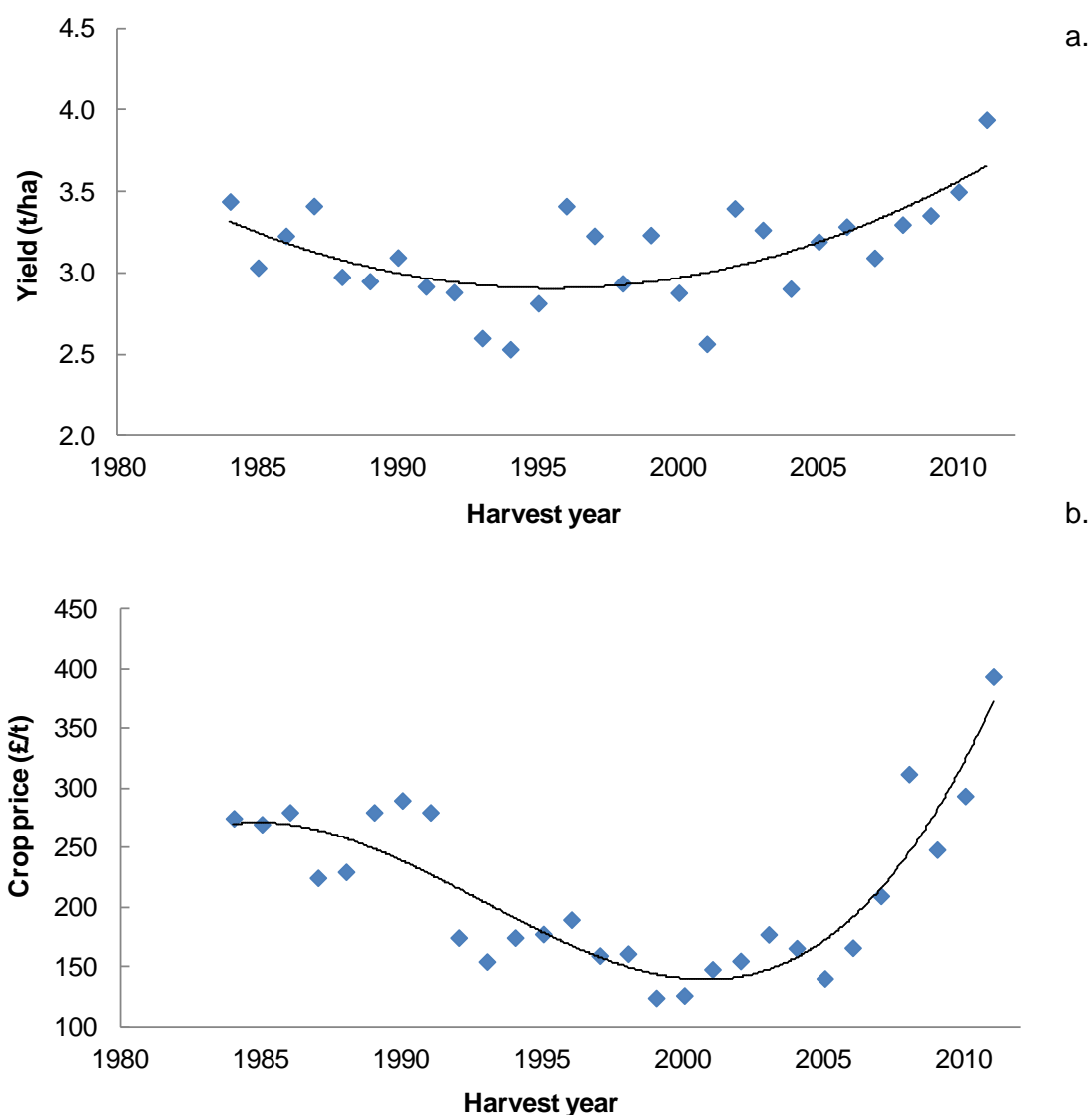


Figure 92. National yield data (a) against market prices (b) for oilseed rape.

In order to explore the relationships between the factors outlined above a regression analysis was run on causal factors against yield change over the 1988 to 2011 period. A number of regressions were explored and table 21 shows the results of a simple OLS regression with lagged prices to explain the effect on yield. This generated an R^2 of 0.38, which indicates that over 60% of the variation in yield is not explained by prices or policy changes.

Table 21. Results of regression on oilseed rape yields

OSR Yield	Coef.
Intercept	-0.05
Price(OSR _{t-1})	0.07
d93 MacSharry	0.01
d05 decoupling	0.13*

As with wheat, when taking the time period as whole, regression analysis failed to indicate a significant short or medium-term impact of crop price change on oilseed rape yields. However, a subsequent analysis showed that for the period from 1984 to 1994, characterised by falling prices and declining yields (Figure 92), crop price and yield were highly correlated ($r = 0.767$, $p < 0.01$). No correlation was found for the middle period but it is assumed that continuing low prices would have acted as an incentive to moderate inputs. Since 2000, with a trend towards rising prices, a relationship between crop price and yield has re-emerged ($r = 0.661$, $p < 0.05$).

There is evidence that policies have had a strong indirect influence on yields. Unlike wheat, the MacSharry reform was not highlighted as being significant in the regression analysis. However, the spike in the area of spring oilseed rape grown in the mid-1990s partly resulted from the introduction of the Arable Area Payment Scheme, which made the lower inputs of spring rape more attractive, despite the lower yield potential, once this was offset by the crop subsidy.

Decoupling of payments in 2005 did not have a significant positive impact. Barnes *et al.* (2011) could find no effect of these reforms on technical change; however management studies have suggested that removing payment for specific production levels would allow freedom to grow according to market demand. These findings are, to an extent, surprising. The sharp drop in crop price in the early 1990s, albeit offset by the introduction of area payments, certainly created a perception of a need to decrease inputs and triggered a move towards an increase in the use of farm saved seed, non-Recommended varieties and spring oilseed rape, as well as the uptake of autocasting and reduced tillage systems all with potentially negative yield impacts.

Farm Business Survey data show that between 2004 and 2009 oilseed rape gross margins were highest for farms in the top yield quartile and lowest for farms in the bottom yield quartile. The differences were smallest in 2005 when oilseed rape prices were at their lowest (Figure 93).

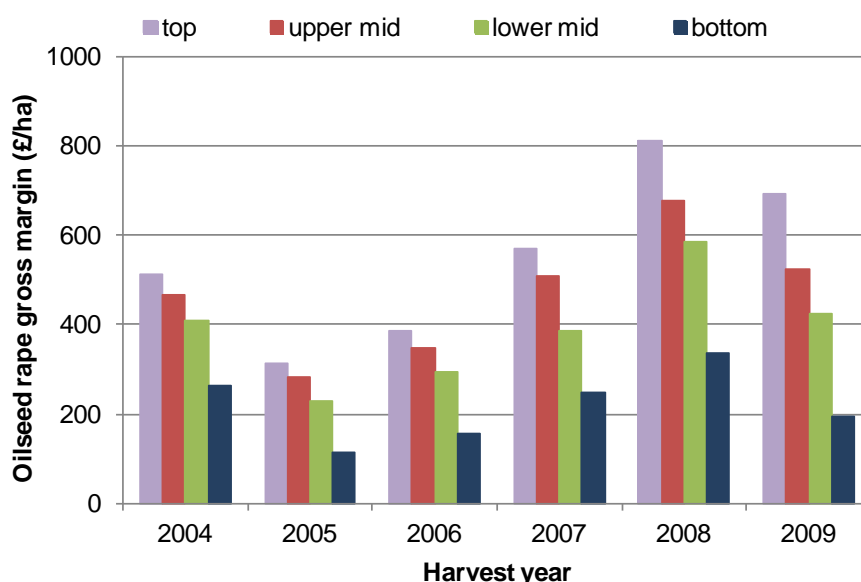


Figure 93. Mean oilseed rape gross margins achieved by FBS top, upper middle, lower middle and bottom yield quartiles.

Over the 2004-2009 period, labour, contract and machinery (rental, depreciation, repairs and fuel & oils) costs per hectare have been higher for farms in the top oilseed rape yield quartile than for the bottom quartile (Figure 94). In addition, since 2004, costs have increased more rapidly for those in the top yield quartile than the bottom quartile, with the difference increasing from about £70/ha in 2004 to over £200/ha in 2009. This could mean that farms in the top yield quartile are investing more in the production of the crop, resulting in better timeliness and field efficiency, although they may also have other enterprises that are influencing the requirement for labour and machinery.

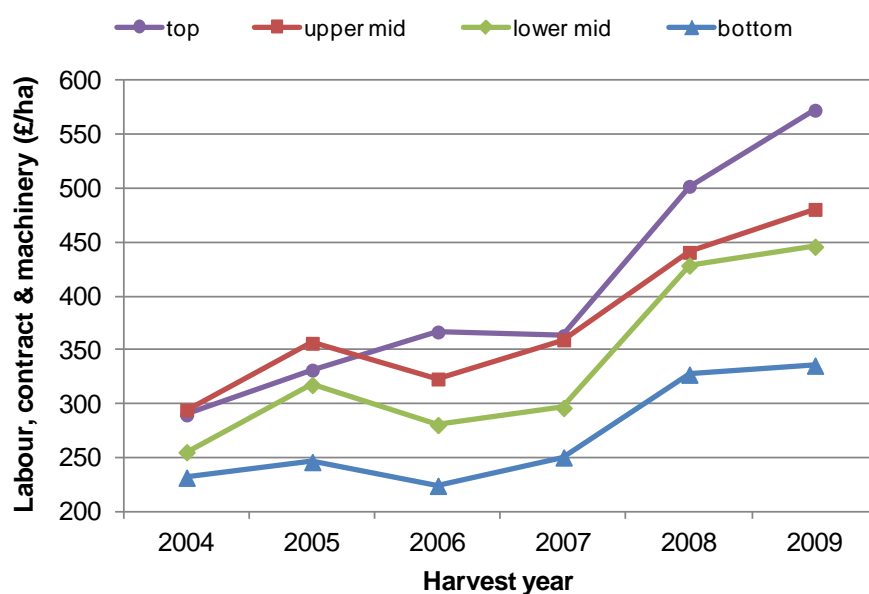


Figure 94. Labour, contract and machinery spend by FBS top, upper middle, lower middle and bottom oilseed rape yield quartiles.

Deducting labour, contract and machinery costs from gross margins for each quartile, it is evident that farms in the top quartile for yield have consistently achieved the best margin, and those in the bottom quartile the poorest margin. However, in some years the differences in margin between top, upper and lower middle yield quartiles were small (Figure 95).

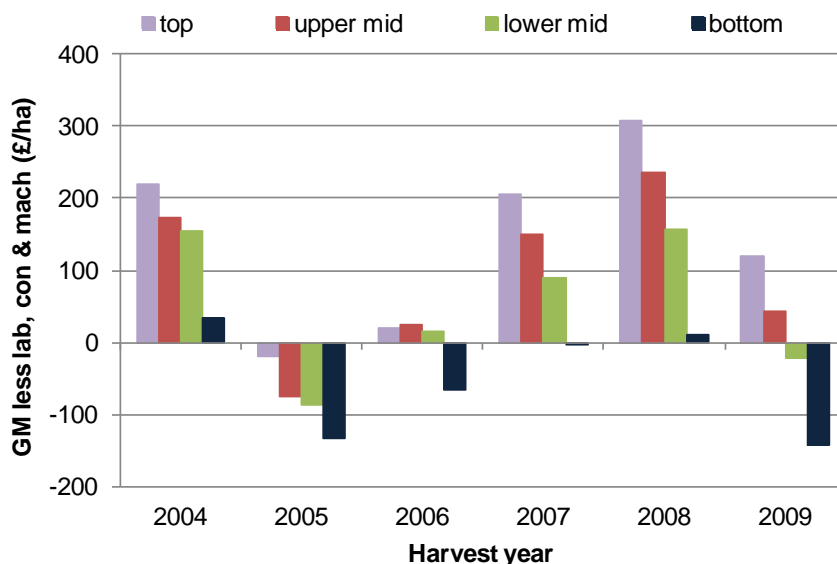


Figure 95. Gross margin less labour, contract and machinery costs for FBS top, upper middle, lower middle and bottom oilseed rape yield quartiles.

3.5.6. Crop nutrition and fertiliser use

Nitrogen

Data from the British Survey of Fertiliser Practice show that overall rates of N application to oilseed rape crops declined steadily from 270 kg N/ha in 1983 to 179 kg/ha in 1994, before rising a little to current rates of around 190-200 kg N/ha (Figure 96). A reduction in the use of autumn N, both in terms of the percentage of crops treated and the average rate applied to treated crops, contributed to the decline in N application. In 1983, 88% of crops were treated with autumn N at an average rate of 52 kg N/ha. According to the British Survey of Fertiliser Practice only 30% of crops currently get autumn N, at a rate of around 33 kg/ha, although 43% of respondents to an on-going AHDB-HGCA survey have indicated that they regularly apply autumn N, at an average rate of 36 kg N/ha (Paul Gosling, personal communication). Assuming that all crops receive N fertiliser in spring, it can be estimated that the average rate applied in the spring declined from 226 kg N/ha to a low of 162 kg/ha in 1994, before rising slightly to a relatively stable value of 180-190 kg N/ha.

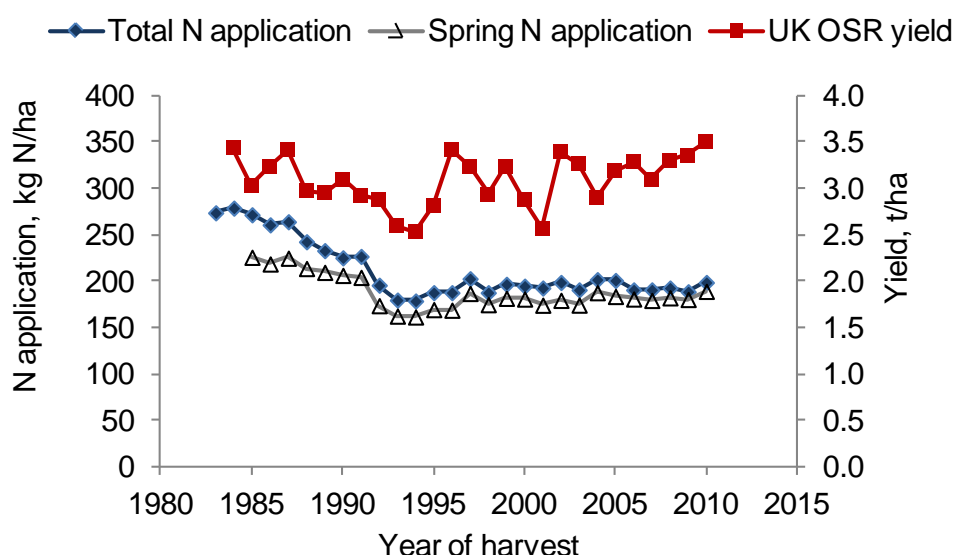


Figure 96. Average total and spring N fertiliser rates applied to oilseed rape and UK average yields.

The decline in N fertiliser applications during the 1980s and early 1990s coincided with a significant reduction in average yield, and was associated with a large reduction in crop price (around 75%) from 1983 to 1998 (Figure 92), which had an impact on the BER for N fertiliser and consequently the economic optimum N dose. In the 1980s the BER adopted was in the order of 1.3:1 (Chalmers, 1987). Current N fertiliser recommendations for oilseed rape are based on a BER of around 2.5:1 (Defra, 2010a). This increase in BER would equate to a reduction in the economic optimum N dose of about 50 kg N/ha (Defra, 2010a). Interpolating between typical N response curves published in the 1980s (Chalmers, 1987) and more recently (Berry & Roques, 2011, Berry *et al.*, 2012), the reduction in spring N dose of about 60 kg N/ha between the mid-1980s and mid-1990s is estimated to have reduced yields by about 0.2 t/ha, equivalent to a yield decline of 0.02 t/ha per year.

There is some evidence that elite oilseed rape varieties differ in their N requirement, with optima varying by 30-100 kg N/ha depending on the year (Berry *et al.*, 2011). The greater N optima of some varieties may be related to poorer N use efficiency, as the N optimum of a variety was negatively related to its yield in the absence of N fertiliser. At present it is not known whether plant breeding has led to an overall increase in N use efficiency of modern compared to old varieties, or whether the N requirement of modern varieties has risen with their yield potential. A study looking at variety yields in reduced N input situations (Kightley, 2010) indicated that tall, vigorous hybrids perform relatively well in a low-N regime compared with short conventional varieties but then fail to respond to increasing N dose as well as the lower biomass types. It was concluded that this might be attributable to better rooting and scavenging for water and nutrients by taller variety types in the low N treatments. Berry & Spink (2009) showed that delaying N applications could increase yields in crops with a high risk of lodging, caused either by growing a lodging-susceptible variety or caused by producing an excessively large crop canopy in spring.

A recent survey of farm crops by NIAB TAG collected information on total dose of N fertiliser applied and seed yield for individual oilseed rape fields from harvest 2010. Growers were asked to specify their N dose within a series of bands. The largest number of fields received between 180 and 209 kg N/ha, consistent with the current national average of 190-200 kg N/ha. However, there was a clear positive relationship between total N dose and the average yield achieved (Figure 97).

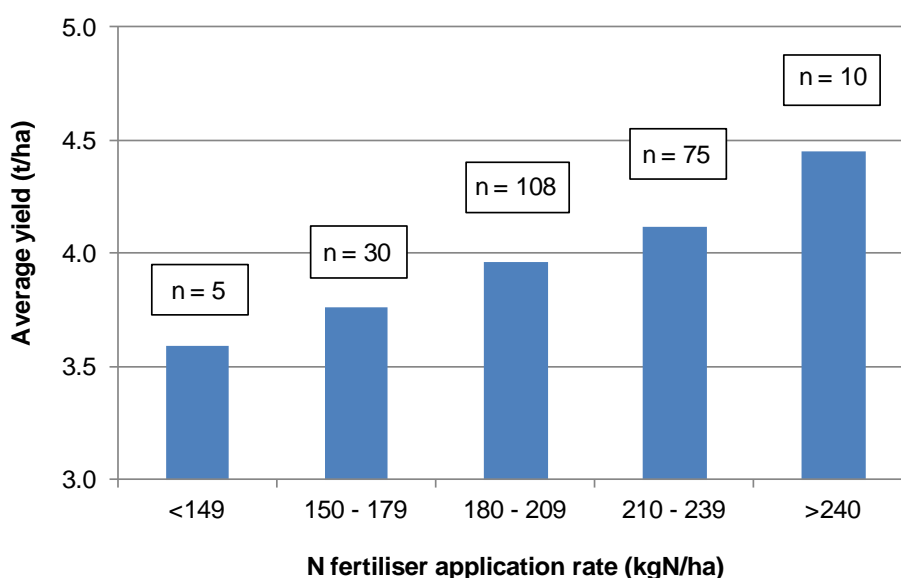


Figure 97. Average oilseed rape yields achieved within farm fields relative to total N dose applied.

Taking the three middle N dose bands only, and the midpoint N dose within these (164 = less than the national average, 194 = close to the national average and 224 = above the national average) it is possible to compare average margin over fertiliser N costs for each band at different ratios of N to oilseed rape price (Table 22). In the majority of cases, with a BER of 5:1 or less, highest margins over fertiliser N cost were achieved in fields receiving the highest of the three N dose bands.

Table 22. Average margin over fertiliser N cost for farm fields receiving N doses within one of three bands, represented by midpoint N doses of 164, 194 and 224 kg N/ha.

OSR price £/t		120			240			360		
N Price £/kg		0.40	0.80	1.20	0.40	0.80	1.20	0.40	0.80	1.20
Break-Even Ratio		3.33	6.67	10.00	1.67	3.33	5.00	1.11	2.22	3.33
N Dose kg N/ha	Yield t/ha	Margin over cost of N fertiliser (£/ha)								
164	3.76	386	320	254	837	771	706	1288	1222	1157
194	3.96	398	320	242	873	795	718	1348	1270	1193
224	4.12	405	315	226	899	810	720	1394	1304	1214

The Defra Fertiliser Manual RB209 (Defra, 2010a) and current NVZ max limits (Defra, 2009) allow additional N to be applied where high yields are expected, and it is possible that not all growers are increasing their N application rates to take account of this and thereby optimise their yields.

Phosphate and potassium

According to the British Survey of Fertiliser Practice, overall rates of application of P and K fertiliser to oilseed rape crops declined steadily from the early 1980s onwards. This is earlier than the decline observed for wheat (Figure 98) and probably reflects a response to the earlier fall in value of oilseed rape compared to wheat.

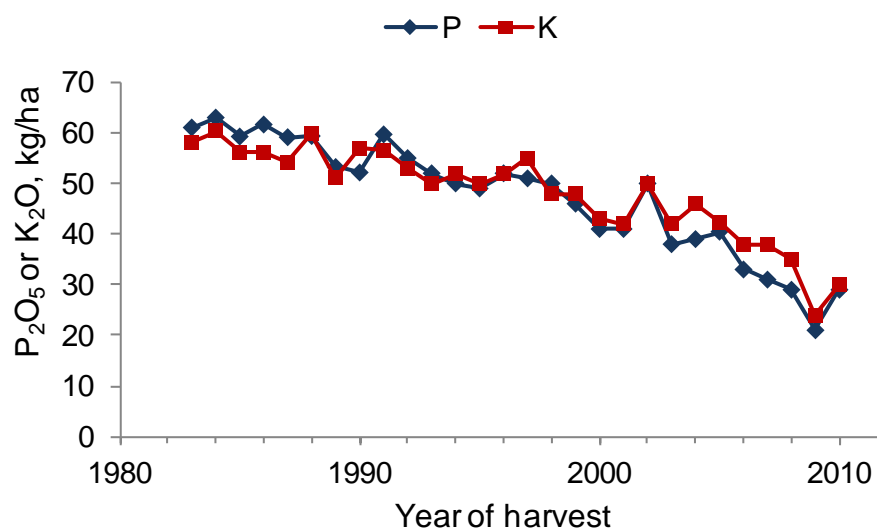


Figure 98. Overall applications of P and K fertiliser to oilseed rape crops.

From the late 1990s the decline in the overall applications of P and K were largely the result of a reduction the percentage of crops being treated (Figure 99). There was also a reduction in average rate of application per treated crop for P, but little overall change in K. In recent years there has been a small increase in the percentage of crops receiving farm yard manure. Estimates of the effects of these overall application rates on the net P_2O_5 and K_2O budgets for oilseed rape crops, assuming that all straw and chaff is incorporated, indicate that there has been net deficit for P_2O_5 from 2003 onwards, but a net deficit for K_2O only from 2008 (Figure 100).

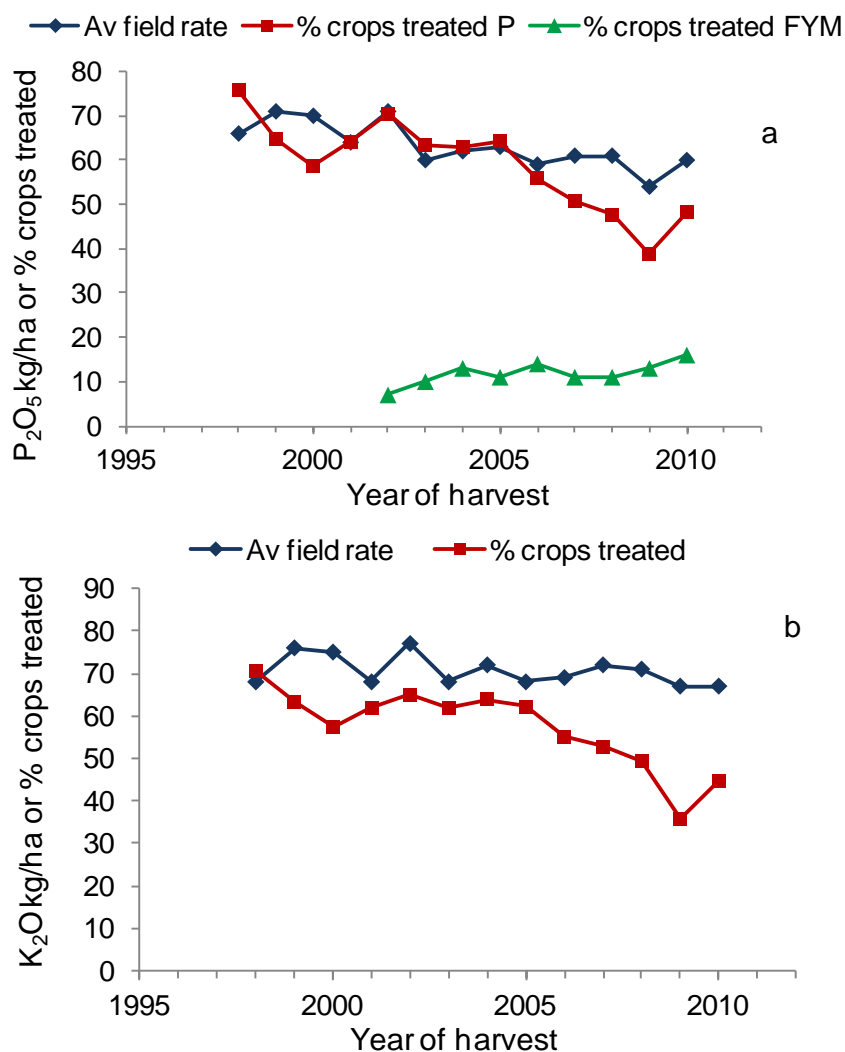


Figure 99. Average application rates per treated oilseed rape crop and % of crops treated with (a) P_2O_5 and (b) K_2O fertiliser.

Between 1998 and 2007, the percentage of crops that were not treated with P and K fertiliser was in general similar to or lower than the percentage of soils above the target P index of 2 and K index of 2-, based on soil samples sent to NRM UK for analysis (Figure 101). More recently, the proportion of untreated crops has exceeded the proportion of soils above the target index by more than 20%, especially for K. As for wheat, the trends in P and K fertiliser application are largely consistent with a nutrient management policy of running down the P and K status of soils to the target index, but do not suggest that average oilseed rape crops are deficient in P and K.

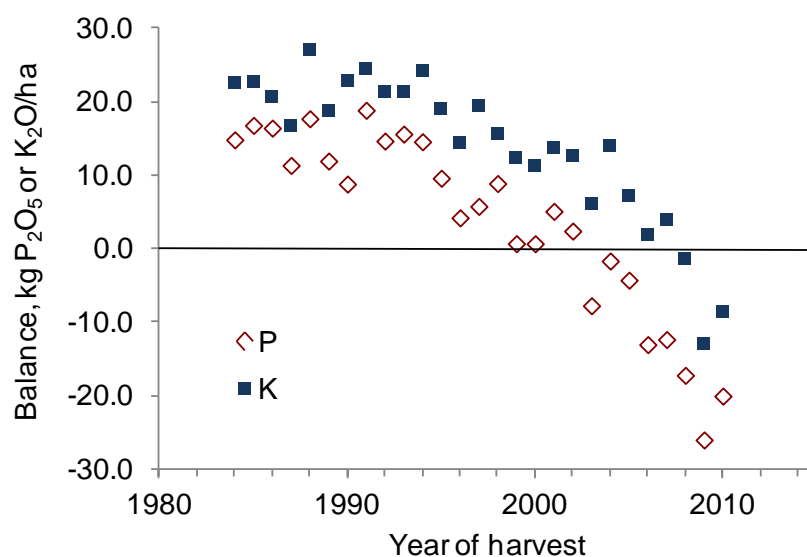


Figure 100. Net budget of P_2O_5 and K_2O applied in fertiliser to oilseed rape crops and that removed in harvested grain.

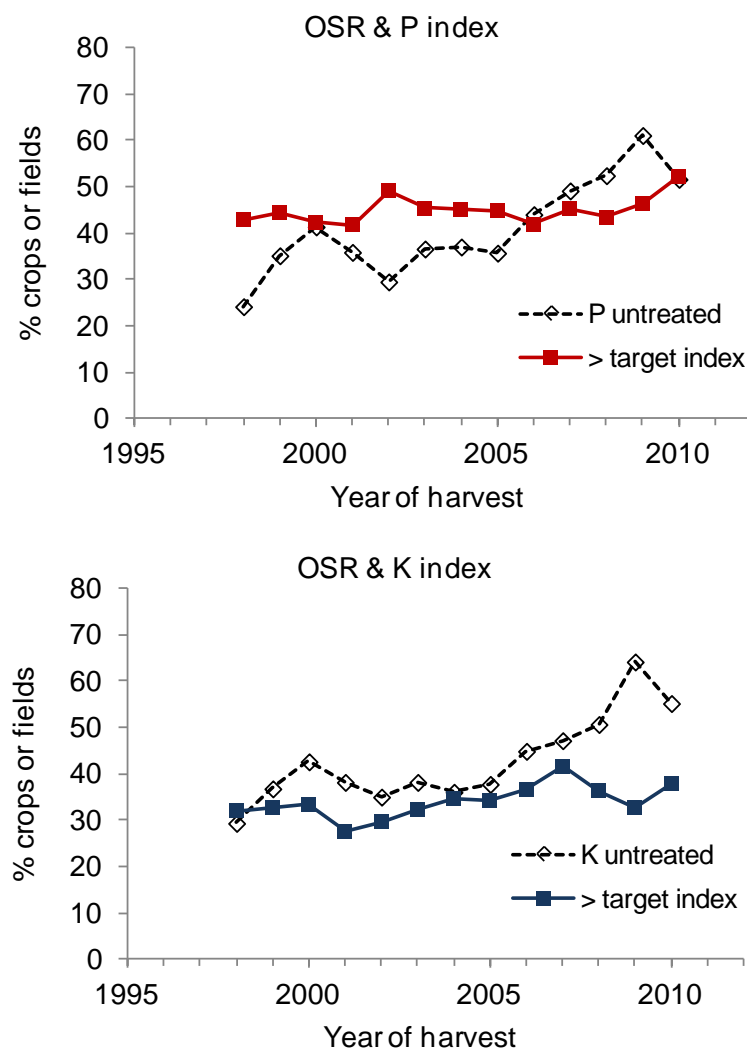


Figure 101. Percentage of oilseed rape crops not treated with P or K fertiliser compared with the percentage of soil samples from arable fields above the target index of 2.

Sulphur

Oilseed rape has a greater sulphur requirement than wheat, with as much as 50-100 kg S/ha being taken up during a season (McGrath and Zhao, 1996). As such it is more susceptible to S deficiency where supplies are restricted. The trend in S fertiliser use is similar to that described for wheat in section 3.4.8. Average application rates have risen from about 40 kg SO₃/ha in 1993 to the current 80 kg SO₃/ha. The percentage of crops treated with S fertiliser rose from less than 5% in 1993 to around 30% during the late 1990s (Figure 102). Another increase occurred from 2001 to 2003, to the current level of 60-70% of crops treated.

With a two-fold greater requirement for S (Defra, 2010a), the proportion of the oilseed rape area at high deficiency risk is greater than that for wheat. Based on estimates from a simple model, McGrath & Zhao (1995b) predicted that, by 2002, 50% of the UK land area would have a high risk and 20% a medium risk of S deficiency for oilseed rape. As discussed in section 3.4.8 for wheat, these estimates did not account for the distribution of arable land in the UK, and therefore are likely to have underestimated the proportion of land growing oilseed rape that was at risk. Using a similar adjustment for oilseed rape as used by Cussans *et al.* (2007) for wheat, it is estimated that the area of oilseed rape at high risk of S deficiency may have been closer to 60% by 2002.

In the early 1990s the oilseed rape area at high risk but not treated is estimated to have reached up to 30%. By the early 2000s this had fallen to less than 10% and since 2004 the area treated has been at least equal to the area thought to be at high deficiency risk, although there is no certainty that the crops being treated are those at highest risk. The oilseed rape area at medium or high deficiency risk is now considered to be so great that all crops should be treated (HGCA, 2005).

Carver (2005) reported that, in an analysis of winter oilseed rape trials conducted between 2000 and 2004, 30% of crops showed significant responses to S fertiliser, with an average increase in seed yield at responsive sites of 44% (range 15-81%). However, two-thirds of these were located on the same highly responsive site. Averaging across varieties and years within each site indicates a more typical yield increase of about 33%. It is estimated that S deficiency may have reduced the national average yield by up to 0.4 t/ha in the early 1990s. It is assumed that the reduction in yield increased between the 1980s and early 1990s in line with the area at risk from S deficiency, but it has not been possible to quantify the rate at which this occurred with certainty. By the early 2000s the estimated national yield reduction had fallen to nearer 0.1 t/ha. This would equate to a positive contribution to yield improvement of about 0.027 t/ha per year between 1994 and 2004. Since 2005 it has been recommended that all winter oilseed rape crops should be treated with S (HGCA, 2005), and it is not known whether a reduction in the national yield is still occurring.

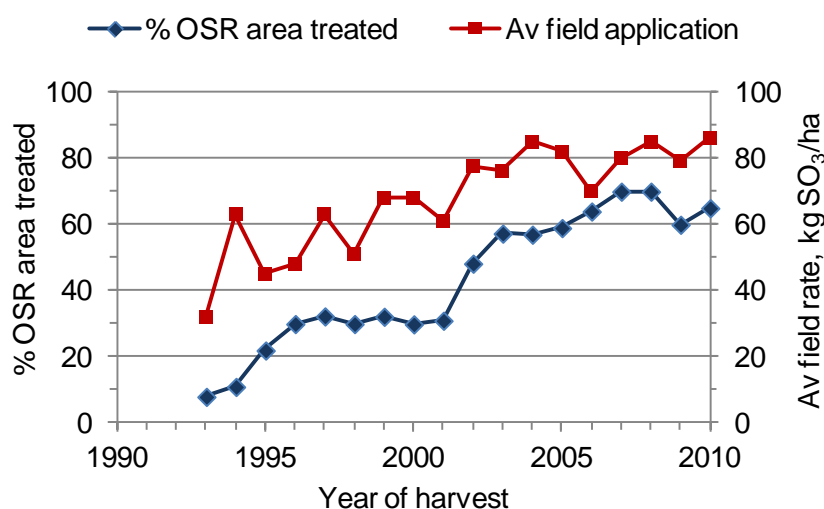


Figure 102. Percentage of oilseed rape area receiving S fertiliser and average field application rate.

Secondary/trace elements and pH

Deficiencies of secondary macronutrients or trace elements are sometimes identified as possible constraints on yield. Magnesium (Mg), manganese (Mn), Boron (B) and Molybdenum (Mo) are of most relevance in oilseed rape. Mg deficiency is most common on light sandy and thin chalk soils. Lasting symptoms are most likely to occur where the soil Mg Index is low (index 0) but transient symptoms can appear when rooting is restricted or in drought conditions. To prevent yield loss, it is recommended that a soil Mg Index of at least 1 is maintained unless more responsive crops are being grown in the same rotation (Defra, 2010a). As described for wheat, data soil samples sent to NRM show that on average only 3% of samples have been at soil Mg Index 0, with no increase from 1995 to 2010. 75% of samples have been at soil Mg Index 2 or above. Transient symptoms have been reported in recent dry springs but there is no evidence to suggest a trend towards increasing Mg deficiency that is likely to have impacted upon national oilseed rape yields.

Mn deficiency occurs mainly on organic soils or sandy soils with high pH. Transient deficiencies may appear where root uptake is poor due to dry 'fluffy' seedbeds or waterlogging. B deficiency is most common on light or leaching prone soils with a pH above 6.5, and is exacerbated by dry seasons. Uptake and translocation of B can also be reduced by low temperatures in the rooting zone. Soil analysis is the best way to identify deficiency risk, although leaf analysis can also aid diagnosis. Mo deficiency is most likely on acid soils as these have low Mo availability.

No survey data could be found to assess changes in the average Mn, B or Mo status of UK oilseed rape crops over time. No published independent data on yield responses to application of Mn, B or Mo were found either. Unpublished results from four trials carried out by NIAB TAG in the 1990s on heavy land in England showed an average yield benefit of 0.18 t/ha (range 0.04-0.24) from the application of B or a B/Mo mixture to oilseed rape at early stem extension. Average yield benefits to Mg and Mn applied at the same timing were 0.10 t/ha and 0.05 t/ha respectively. B was the only

element to give a significant yield increase in any trial. However, there is insufficient evidence to link changes in nutrient status of oilseed rape crops to the observed trends in national yield.

The optimum soil pH for oilseed rape is about 7.0, slightly higher than for wheat. Samples analysed by NRM showed that an average of about 40% of arable fields were within the pH range 6.5 to 7.5, with no change between 1995 and 2010. Between 1995 and 2007 the proportion of samples with a pH below 6 doubled from 10 to 20%, with a fall in the proportion of samples above pH 7.5. If representative of the UK as a whole, an increase in fields with a mean pH below 6 could have had a small negative impact on the national oilseed rape yield trend between 1995 and 2007, either directly or through a greater risk of clubroot or Mo deficiency. From 2007 to 2010 the increase in samples below pH was reversed, and could therefore have had a small positive impact on yields.

Differences between farms

Farm Business Survey data show that farms in the top oilseed rape yield quartile are spending slightly more per hectare on fertiliser than farms in the bottom quartile (Figure 103), although the gap between the top and bottom quartiles has been relatively small until recently. Farms in the top quartile for oilseed rape gross margin are typically spending less on fertiliser than farms in the bottom quartile, although not in 2004 and 2007 (Figure 104). This doesn't necessarily mean that farms in the top gross margin quartile have been using less fertiliser (they may have been buying more competitively) or that farms in the top gross margin quartile have limited their yields (they may have had a lower fertiliser requirement).

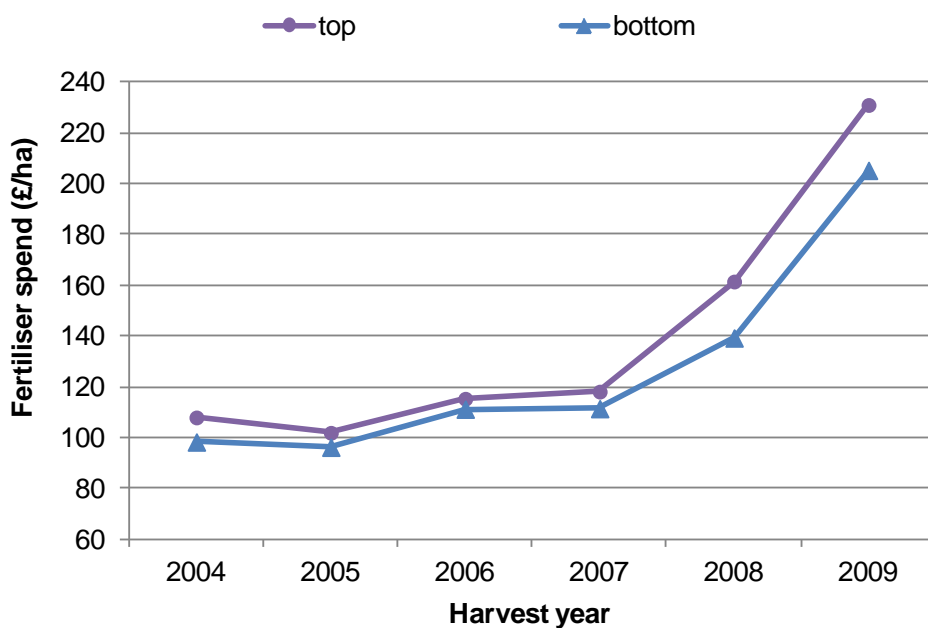


Figure 103. Fertiliser expenditure for FBS top and bottom quartiles for oilseed rape yield.

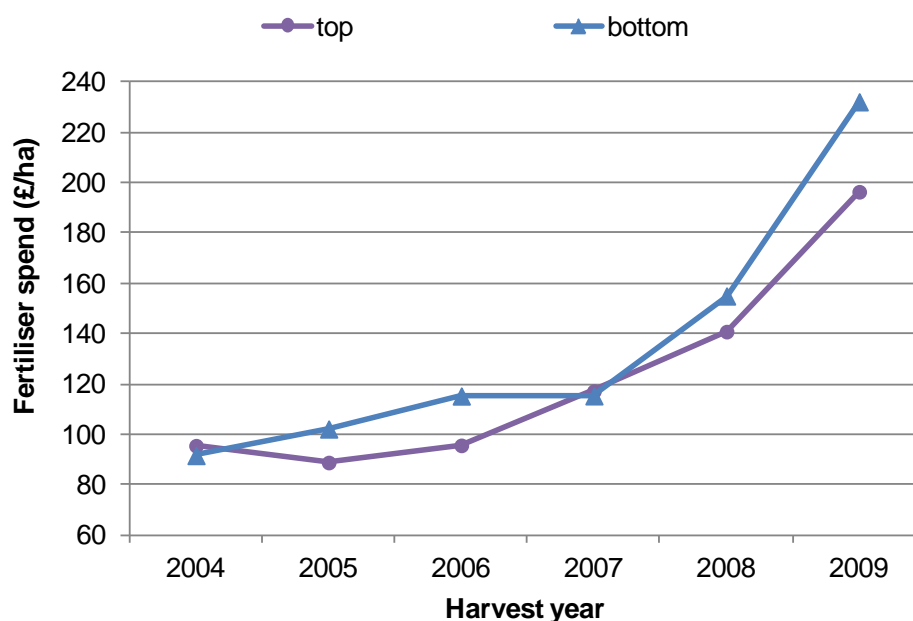


Figure 104. Fertiliser expenditure for FBS top and bottom quartiles for oilseed rape gross margin.

3.5.7. Crop protection and pesticide use

Varying amounts of information were available for analysing changes in crop protection for oilseed rape over the last 25 years. Disease data were available from CropMonitor for all years since 1987. The survey also provided information on fungicide and insecticide use for the same crops and over the same period, plus detailed information on autumn and spring pest levels starting in 2004/05. Data for the use of other pesticides were accessed from Pesticide Usage Survey reports, which were available back to 1998.

Foliar, stem and pod diseases

Booth *et al.* (2005) highlighted disease generally, and light leaf spot (*Pyrenopeziza brassicae*) in particular, as prime suspects in the yield variability of commercial crops and their failure to match the upward trend seen in RL trials. This was blamed on poor varietal resistance and the failure of fungicides to give adequate control. In England the proportion of plants affected by light leaf spot in spring, and the proportion of stems affected by light leaf spot in summer have tracked one another closely, but have varied widely, undergoing a series of peaks and troughs about every eight years (Figure 105). With a potential yield loss of 10% for every 30% of plants infected in spring (Su *et al.*, 1998), for the crops surveyed since 1987 this would equate to a range in potential lost yield of less than 1% (0.02 t/ha) to more than 15% (0.5 t/ha), if the disease was not treated. Clarke *et al.* (2009) estimated the potential annual loss of production with current treatments as 58,000 tonnes (3%).

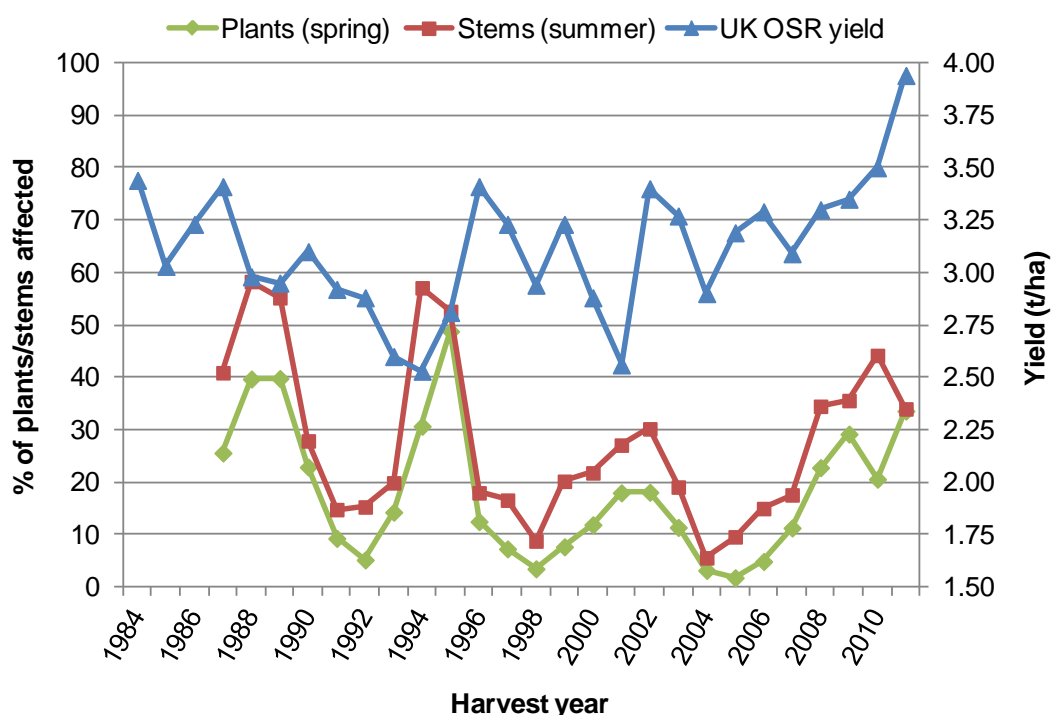


Figure 105. % of plants (spring) and stems (summer) affected by light leaf spot for commercial oilseed rape crops in England.

There is little indication that years of high light leaf spot levels were years of low yield, or vice versa. It is evident that yields have been rising since 2004 despite increasing levels of light spot. However, the average leaf area affected in a year does not always reflect the % of plants affected.

The proportion of plants affected by Phoma leaf spot (*Leptosphaeria maculans*) in the autumn and the proportion of stems affected by Phoma stem canker in the summer (only recorded since 1999) have tracked one another reasonably well (Figure 106). There are indications of a generally higher incidence of Phoma in the period between the mid-1990s and mid-2000s, but with levels in the last four years at their lowest since the early 1990s, which coincides with the recent rise in yields.

Clarke *et al.* (2009) estimated the potential annual loss of oilseed rape production due to Phoma as 88,000 tonnes (4.5%) even with current treatments. However, the disease data do not suggest an overriding influence of Phoma leaf spot and stem canker on the national yield trend.

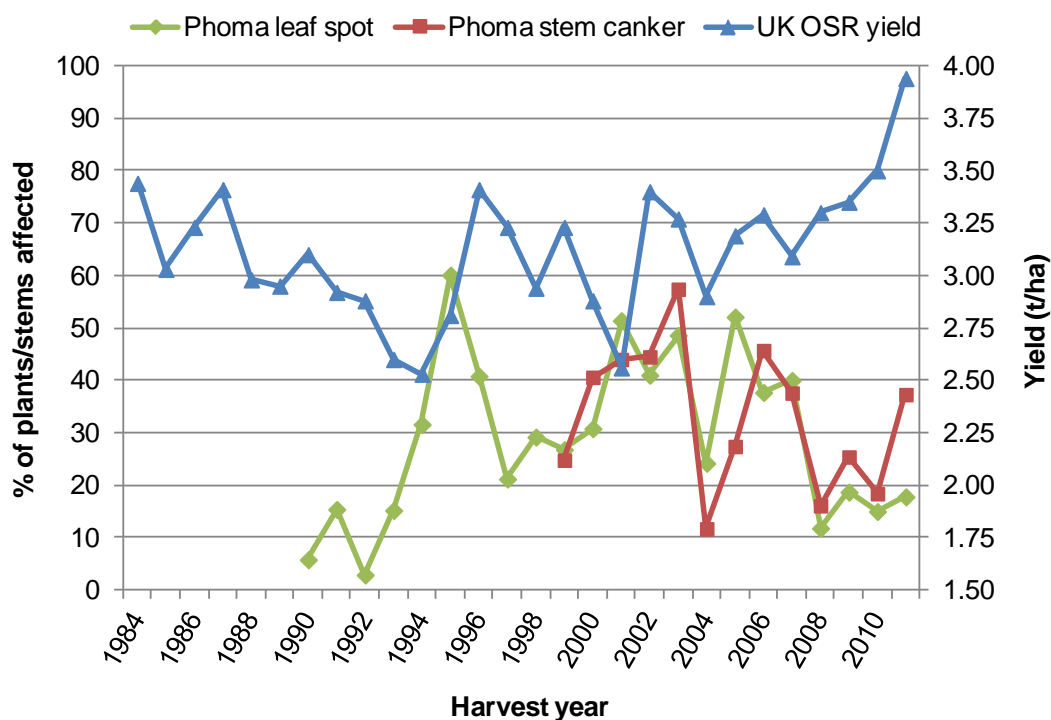


Figure 106. % of plants affected by Phoma leaf spot in autumn and % of stems affected by stem canker in summer for commercial oilseed rape crops in England.

The incidence of *Sclerotinia* (*Sclerotinia sclerotiorum*) has been very variable; as has the % of pod area affected by all diseases during pod fill (Figure 107). Again there is little indication of a clear association between either of these and the yield trend, although it is noted that the last three years during which yields have risen have experienced the lowest combined levels of *Sclerotinia* and pod diseases since 1996. Clarke *et al.* (2009) estimated the potential annual loss of oilseed rape production due to *Sclerotinia* as 22,000 tonnes (about 1%) with current fungicide treatments.

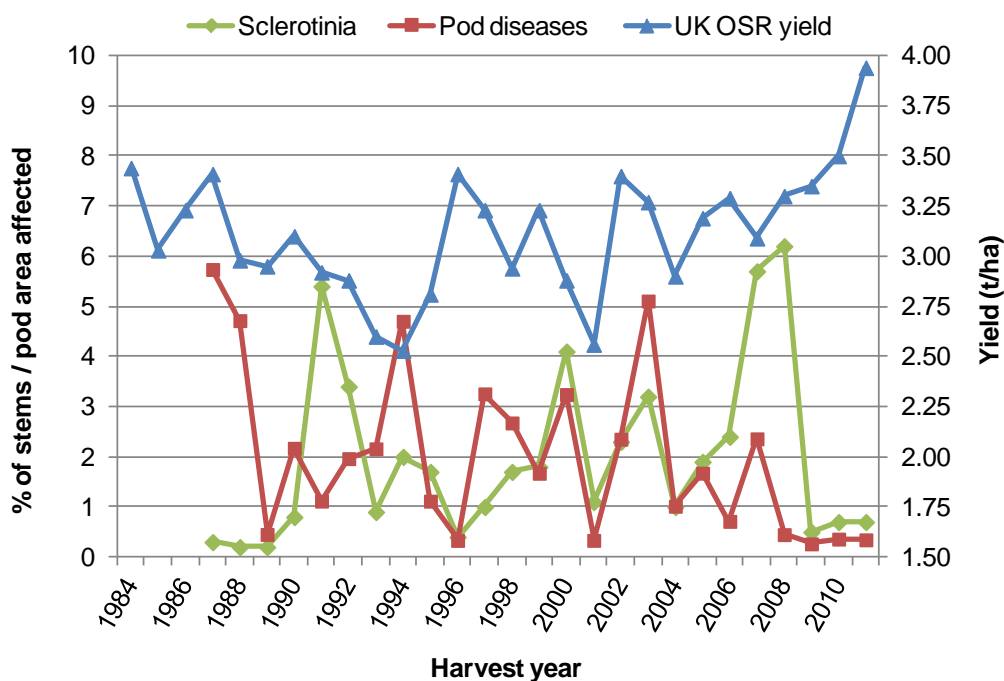


Figure 107. % of stems affected by *Sclerotinia* and % pod area affected by all diseases in summer for commercial oilseed rape crops in England.

Two other soil-borne diseases are a potential threat to oilseed rape. The first is Verticillium wilt, caused by *Verticillium longisporum*. First confirmed in the UK in 2007, it appears to be established in southern and central England with an incidence ranging from 1-90% of plants affected in fields monitored in 2007 and 2008 (Gladders, 2009). The disease causes premature ripening, with yield losses of up to 50% in Europe, although damage varies from year to year according to seasonal weather (increased by higher temperatures from flowering through to maturity and later by drought stress). Earlier sowing, short rotations and non-inversion cultivation have been linked to increased occurrence of Verticillium wilt in Germany (Kreye *et al.*, 2006). The second disease is clubroot (*Plasmodiophora brassicae*), which is most prevalent in Scotland and the west of the country. Yield losses of 0.03 t/ha per 1% of plants infected are reported (HGCA, 2011). Short rotations, flooding, early sowing and warmer, wetter autumns and springs increase risk on farm. A longer rotation offers the most durable control strategy. Varietal resistance can give good control but this may fail in fields where resistant varieties have been grown previously. Raising soil pH and calcium content can also reduce disease severity. The extent to which either disease may have increased in incidence or severity over time is unclear, so their effects on national yield trends are unknown.

Pest control

British Trust for Ornithology survey data estimate wood pigeon numbers for 2010 at between 2.6 and 3.2 million birds (<http://blx1.bto.org/birdtrends/species.jsp?s=woodp>). Numbers have risen consistently since the mid-1970s, approximately trebling. BTO report that there is some evidence to link this increase to the spread of intensive winter cereal and oilseed rape cultivation, probably by increasing food availability over the winter, reflecting the species' ability to subsist on green vegetation, unlike other granivores. The data also suggest a steady lengthening of the laying season. After an initial rise in successful fledglings per breeding attempt this trend has plateaued or possibly declined since the mid-1990s but is estimated to be less than one per breeding attempt.

Wood pigeons can pose a major threat to successful establishment of oilseed rape, feeding intensively on fields once the feeding pattern for the season has been established. Actual areas of crop loss have not been estimated nor has yield loss from grazed crops. Flowering from badly grazed crops can be delayed by two to three weeks and the subsequent canopies tend to be much shorter than ungrazed crops of the same varieties in comparable locations. These canopies are often prolifically branched and may hold considerable yield potential but seed set and development through to maturity may progress in more stressed conditions than ungrazed crops, especially in dry seasons, more akin to the growth of spring oilseed rape.

Information collected by CropMonitor on the number of larvae of Cabbage Stem Flea Beetle (*Psylliodes chrysocephala* L.) and Rape Winter Stem Weevil (*Ceutorhynchus picitarsis* Gyll.) in

oilseed rape plants in the autumn and spring shows that incidence continues to be low, with few if any sites reaching the appropriate economic threshold for treatment between the 2004/05 and 2010/11 seasons. With current treatments, the estimated annual potential loss in national oilseed rape production due to cabbage stem flea beetle is only 7,000 tonnes (<0.5%) (Clarke *et al.* 2009).

Pollen beetles (*Meligethes aeneus*) are a potential threat to yield when they move into an oilseed rape crop before flowers start to open, and bite into the buds, killing them. Data collected as part of the CropMonitor survey of farm crops across England reveal that between 1988 and 2006 the average number of pollen beetles has remained below 5 per plant in nearly all years. There is also little indication of any rising trend in pollen beetle numbers over that period, but despite this an increasing proportion of farm crops have been receiving an insecticide spray at flowering since 2002 (Figure 109). Although pollen beetle damage will undoubtedly account for some loss of yield in some crops, if anything this is likely to have decreased in recent years.

Most oilseed rape crops produce more buds and flowers than are needed, so some can be lost before yield is affected. Recent research (Ellis & Berry, 2012) has indicated that oilseed rape crops with lower plant populations may have a higher threshold per plant than crops with higher plant populations. However, this does not mean that crops with a low plant population are less at risk from a given number of pollen beetles per unit area, and it also assumes that a crop that is thin is able to branch adequately to compensate. With pyrethroid-resistant pollen beetles present in many areas of the country, it is vital that control treatments are targeted appropriately. It is reported that in 2006 a failure of pyrethroids to control pollen beetles in Germany ruined 30,000 ha of winter oilseed rape and caused serious losses in a further 200,000 ha (Slater *et al.*, 2011).

Autumn aphids (predominately *Myzus persicae*) causing Turnip Yellow Virus (TuYV) are reported to be capable of decreasing yield by up to 26% (Stevens *et al.*, 2008). In the early 1990s average plant infection rates of TuYV in the UK ranged from 49 to 73% (Hardwick *et al.*, 1994). Although annual incidence is variable there is little evidence to suggest a consistent increase. Nevertheless it has been suggested that TuYV may have had a negative impact on the oilseed rape yield trend. (Stevens *et al.*, 2008). Clarke *et al.* (2009) estimated the potential annual loss of production due to TuYV as 58,000 tonnes (3%) even with current treatments. Due to high levels of resistance in *M. persicae* to insecticides currently approved for autumn use in oilseed rape, up to 80% of aphid populations may not be controlled (Stevens *et al.*, 2008). Pesticide Usage Survey data show that the proportion of the oilseed rape area that received seed treatments containing imidacloprid had reached nearly 70% by 2006. With the introduction of seed treatments containing clothianidin or thiamethoxam, which have greater activity against aphids, the oilseed rape crop area that received an insecticidal seed treatment had increased further to nearly 80% in 2010.

Oilseed rape may be infected by a number of nematode species, though their national significance and contribution to yield depression is unknown. The most recent investigation has focused on two species of cyst nematode which infect oilseed rape, *Heterodera cruciferae* and *H. schachtii*. Pot experiments have shown that *H. schachtii* is capable of two generations per year on oilseed rape, and has the potential to increase under closer rotations (HGCA Annual Report 2011 Project 3478). Further aspects of this study will determine distribution of the nematode in oilseed rape growing areas. *H. schachtii* also infects sugar beet and a current BBRO funded study is surveying incidence and severity in beet growing areas. Since these are concentrated in the eastern half of England, it is possible that oilseed rape will be grown in rotation with some sugar beet crops, so this survey may provide additional information relevant to oilseed rape. *H. cruciferae* infects vegetable brassicas as well as oilseed rape. Harris & Evans (1988) reported yield increases of 0.66 t/ha in oilseed rape varieties when these were grown in an infested field and treated with a nematicide. However, there is little information available on the distribution of the species.

Recently, an outbreak of the root knot nematode, *Meloidogyne artiella* has been confirmed in an oilseed rape crop showing patches of stunting and poor growth (Thomas, 2012, unpublished). This nematode is known to occur on brassicas, cereals and pulses in the UK and, though confirmed incidences are comparatively rare, it may be affecting crop productivity in the absence of obvious symptoms. Free living nematode species (*e.g. Pratylenchus* and *Ditylenchus*) may also invade and feed on oilseed rape roots. Populations of pathogenic nematodes have been detected under different rotations (Hilton *et al.*, 2011), but the degree of damage caused by these organisms on a national scale is unknown. Infected roots may be less able to utilise available water and nutrients efficiently, and patchy poorly grown areas may at least in part be caused by nematode infestations. The significance of a number of nematode species on crop performance is worthy of further study, not least because the threat they pose could increase as average temperatures creep upwards.

Weed control

As with wheat, no annual survey data were available to evaluate changes in weed populations in oilseed rape. According to Clarke *et al.* (2009), only two weed species are currently estimated to cause potential annual yield losses of 10,000 tonnes (0.5%) or more with available herbicides. These are chickweed (*Stellaria media*) and black-grass. There is little indication that chickweed is an increasing problem. Although black-grass has become progressively more difficult to control in oilseed rape due to rising levels of ACCase resistance, it is unlikely that this would have had a significant direct impact on the national yield trend, although other changes in management practice aimed at maintaining or improving black-grass control may have had an incidental effect.

Pesticide usage

The proportion of crops treated with fungicides in the autumn / winter (mostly targeting Phoma and/or light leaf spot) increased dramatically between 1994 and 2000, and has remained at relatively high levels since (Figure 108). The slight dip since 2008 may be due to expectation of lower Phoma risk as a result of drier autumns, but this may inadvertently have contributed to the increase in light leaf spot being observed in spring. There was a slightly earlier increase in the number of crops treated with fungicides at flowering, starting in 1991, which mainly substituted for post-flowering fungicides, application of which had declined to 5% or less of crops treated by 1992. The trend towards increased use of fungicides at flowering was partly reversed after 1994, and had fallen to half the 1994 level by 2002. As with T3 sprays on wheat, the mid-flower fungicide spray on oilseed rape was commonly a target for cost-saving by growers in response to lower crop prices, due to the uncertainty of achieving a cost-effective yield benefit. This trend was reversed again from 2004, partly as a result of Sclerotinia concerns but also improving economic prospects and the availability of new fungicides offering the potential for improved responses at the flowering timing. It is clear that in recent years, oilseed rape crops have been better protected than ever by fungicides, and a positive contribution to the national yield trend would be anticipated.

The proportion of crops treated with insecticides has also changed over the last 25 years (Figure 109). Between 1987 and 1997 autumn / winter applications increased erratically from less than 10% of crops treated to around 70%. From the 1990s to mid-2000s there were some similarities in the patterns of annual variation for autumn / winter insecticide use and national yields. This is not the case in the last couple of years, but the availability of new neonicotinoid seed treatments with longer lasting activity on a range of insect pests could explain this. The proportion of crops treated at flowering also increased, but more steadily, between 1987 and 1997, and then fell back to pre-1990s levels until starting to increase again in 2003. This follows a very similar pattern to that seen with fungicides applied at flowering, probably due to the tendency for insecticides to be included routinely if travelling through the crop to apply a fungicide, whereas application of an insecticide alone is often only in response to a specific threat or threshold having been reached.

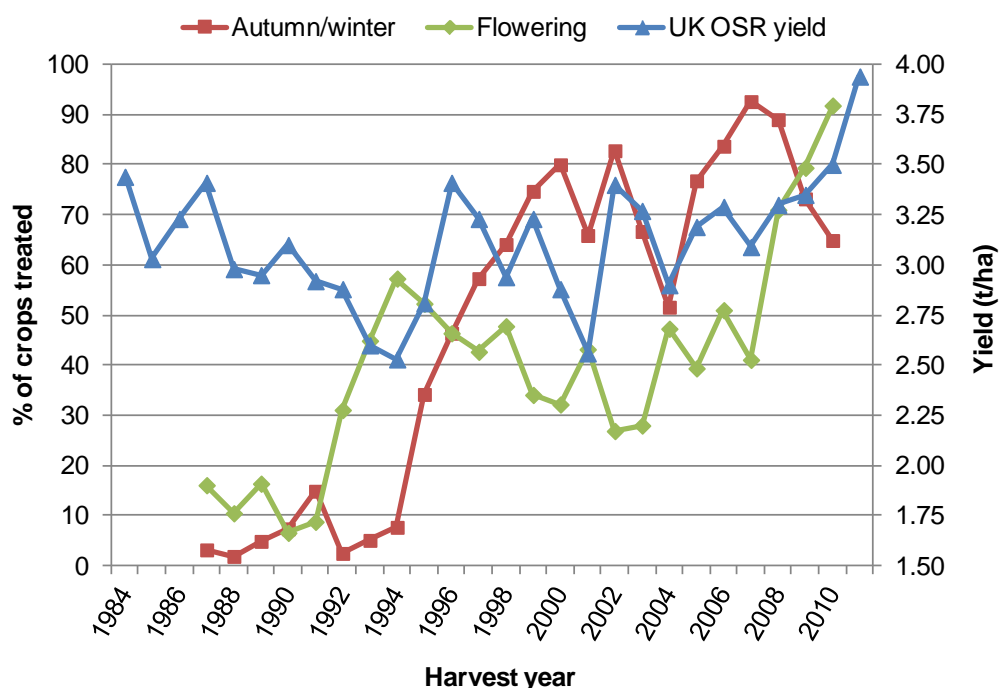


Figure 108. % of commercial oilseed rape crops treated with fungicides in autumn / winter and at flowering in England.

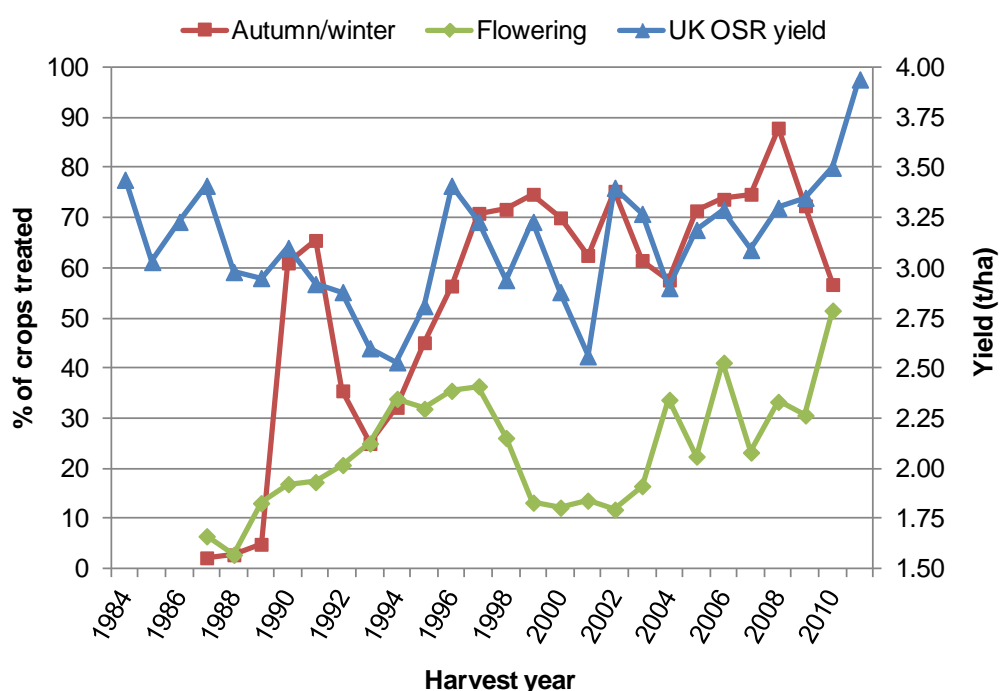


Figure 109. % of commercial oilseed rape crops treated with insecticides in autumn / winter and at flowering in England.

The Pesticide Usage Survey reveals an overall increase in average number of fungicide and insecticide applications to oilseed rape since 2002 (Table 23). It is evident that crops have been better protected against insect pests in recent years than at any time since 1997. More especially, the data show a consistent increase in number of herbicide applications between 1998 and 2008, indicative either of increasing weed problems, associated with herbicide resistant black-grass and

changes to establishment practice, or perhaps a desire to maintain a higher level of weed control. The number of herbicide active ingredients applied has also doubled over the same period, with smaller increases in the number of insecticide and fungicide active ingredients used (Table 24). Together, this paints a picture of increasing investment and sophistication for oilseed rape crop protection, since the early 2000s in particular, which it is reasonable to assume would at the very least have prevented any increase in loss of yield to weeds, pests and diseases.

Table 23. Average number of spray rounds applied to oilseed rape crops in Great Britain.

Harvest year	1998	2000	2002	2004	2006	2008	2010
Group	Number of spray rounds applied to oilseed rape						
Insecticides	1.4	1.3	1.5	1.8	1.9	2.0	1.8
Fungicides	1.9	1.7	1.8	1.8	2.1	2.8	2.6
Herbicides	2.2	2.3	2.7	2.9	3.0	3.6	3.4
Molluscicides	0.3	0.7	0.7	0.4	0.8	1.3	0.6
All pesticides	4.4	4.5	5.0	5.1	5.7	7.0	6.3

Table 24. Average number of active ingredients applied to oilseed rape crops in Great Britain.

Harvest year	1998	2000	2002	2004	2006	2008	2010
Group	Number of active ingredients applied to oilseed rape						
Insecticides	1.5	1.3	1.6	1.9	1.9	2.0	1.8
Fungicides	3.4	2.5	2.9	2.8	3.0	4.3	4.2
Herbicides	2.5	3.0	3.6	3.8	4.1	5.0	5.2
Molluscicides	0.3	0.7	0.7	0.5	0.8	1.3	0.7
All pesticides	7.8	7.7	8.7	9.0	9.8	12.7	11.9

Lodging control

Many of the early double-low winter oilseed rape varieties were tall and prone to lodging, which contributed to their unpopularity with growers. The introduction of Apex in the mid-1990s was a breakthrough, combining high yield with fairly short, stiff stems, enabling the variety to dominate seed sales for an eight year period. Subsequent yield improvement was often accompanied by a reversion to weaker-stemmed types and seed companies began advising lower seed rates for specific varieties in order to reduce lodging risk, and marketing seed in hectare packs to consolidate the message. Consequently seed rates fell from around 120 seeds/m² (7 kg/ha) to about 90-100 seeds (5-6 kg/ha) as growers gained confidence in using this approach.

According to Pesticide Usage Survey reports, the area of oilseed rape treated with non-fungicidal PGRs increased from 10,000 ha in 1988 to 39,000 ha in 1996 but this had fallen to 1,000ha by

2002 as approvals for use of chlormequat products in oilseed rape ended. Since then control of lodging has been achieved through other means, including later application of some N fertiliser, progressively lower seed rates and application of specific fungicides with PGR activity at the green or yellow bud crop stages. These measures have helped to counter the increase in lodging risk due to earlier crop establishment and in seasons with mild winters or wet springs. However, applied inappropriately, delayed N fertiliser (in dry springs) or PGR fungicides (on small or backward canopies, HGCA 2012) have the potential to reduce yield. No data could be found to assess trends over time in the oilseed rape area lodged or estimated yield loss from lodging. However, anecdotally a higher incidence of lodging has been suggested as a factor in the drop in yield of some commercial crops in 2012.

Differences between farms

Data from the Farm Business Survey shows that farms in the top quartile for oilseed rape yield are spending more per hectare on pesticides than farms in the bottom quartile (Figure 110). The gap between the top and bottom appears to have increased over the period analysed, with only a 15% difference in 2004 and 2005 but nearer a 25% difference in 2008 and 2009. It is also interesting to note that expenditure on pesticides for oilseed rape was less than for wheat in 2004 and 2005, but similar to wheat in 2008 and 2009. This suggests that growers have been raising their investment in oilseed rape more than in wheat during the second half of the 2000s, which could be a factor in the diverging picture for their yield trends in recent years.

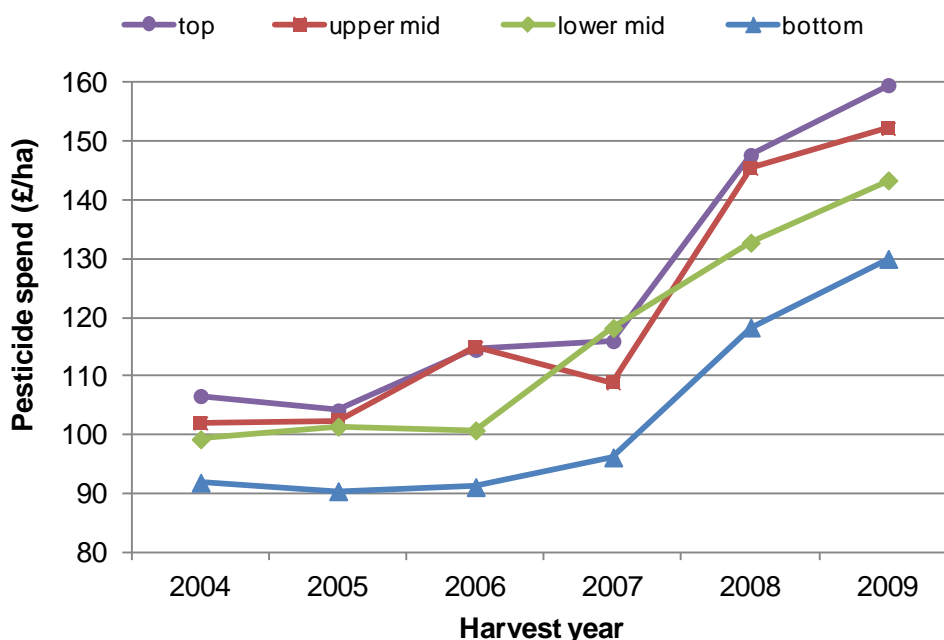


Figure 110. Pesticide expenditure for FBS top, upper middle, lower middle and bottom quartiles for oilseed rape yield.

When comparing quartiles by gross margin (Figure 111), over the period analysed farms in the top quartile have generally been spending slightly less on pesticides than farms in the bottom quartile. This doesn't necessarily mean that farms in the top gross margin quartile have been using fewer pesticides, as they may have been buying them more competitively, or that farms in the top quartile have limited their yields, as they may have had a lower pesticide requirement for example due to more timely application. However, it highlights that the most appropriate level of investment in crop protection to optimise gross margin may have been less than that required to optimise yield.

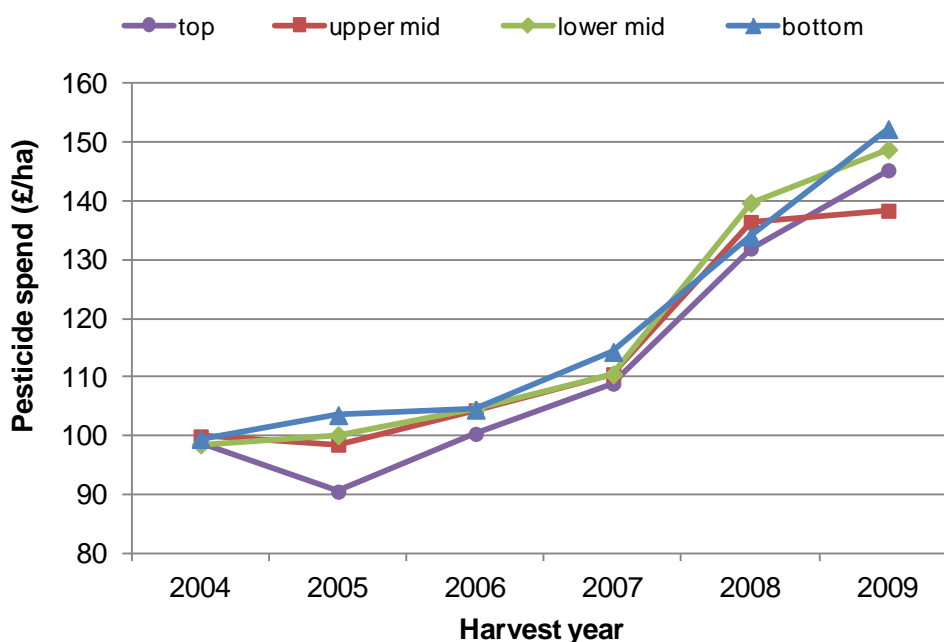


Figure 111. Pesticide expenditure for FBS top, upper middle, lower middle and bottom quartiles for oilseed rape gross margin.

3.5.8. Soil management and cultivations

As evidenced by lateral and forked growth of tap roots, in some situations, oilseed rape is sensitive to compaction. Comparisons between non-inversion tillage and ploughing are more difficult for oilseed rape than for wheat due to a lack of UK based information. Sauzet *et al.* (2003) observed an average 10% yield reduction with minimum tillage and direct drilling compared to ploughing in France, resulting from reduced crop growth caused by straw mulch from the previous crop and poor soil structure at 5-15cm depth. Conversely, in Germany Christen *et al.* (2003) found no significant differences in yield between a range of cultivation approaches, including ploughing, deep (25cm) and shallow (10-15cm) non inversion and direct drilling. However, they too observed that straw management as well as crop rotation were important within minimum tillage systems. Spink *et al.* (2009) suggested that direct sowing led to a 13% reduction in oilseed rape yields compared with ploughing.

Nearly 500 fields of mainly spring turnip rape and some oilseed rape were surveyed in Finland between 2007 and 2009, in order to assess tap root penetration late in the season (Peltonen-Sainio *et al.*, 2011). Crop species, year, soil properties and cultivation method all had an effect. Many fields had less than 30% of roots with restricted penetration, but in some more than 70% of roots were affected. Oilseed rape had a greater proportion of roots with poor penetration of deeper soil layers than turnip rape, and direct-drilled fields had twice as many roots with poor penetration as reduced tillage or fully cultivated fields. Yield loss was linearly related to the incidence of plants with poor penetration in 2007, but not in other years. Nevertheless, it was concluded that rapeseed yield decline may at least partly be related to poor tap root penetration.

For oilseed rape in the winter cropping rotation within the STAR project (Stobart and Morris, 2011), mean yield reductions were 9% and 5% for shallow and deep non-inversion respectively compared to a plough based approach (Table 25). However, this is based on only two years of data, and a different non-inversion technique was used in each year. In 2006, non-inversion was based on a cultivator drill operating at two depths, and a yield penalty was observed. In 2010, when oilseed rape was next grown in the winter crop rotation, non-inversion was based on a tined 'subcasting' system operating at two depths, and there was little or no yield penalty.

Table 25. Oilseed rape crop yields following non inversion tillage compared to ploughing.

Primary Cultivation	Mean OSR yield (% of ploughed)		
	2006	2010	Mean
Plough	100	100	100
Deep non-inversion	89	102	95
Shallow non-inversion	86	97	91

No farm survey data could be found to assess changes in establishment method for oilseed rape, but the shift from ploughing to non-inversion is considered to have been as great if not greater than for wheat. A survey of 228 oilseed rape crops across England by NIAB TAG in 2010 revealed that 40% were established using deep non-inversion systems, 32% using shallow non-inversion, 26% by direct drilling and 2% by autocasting. None were established after ploughing. Much of the initial change in the 1990s was to shallow non-inversion or autocasting. Although saving cost, conserving moisture and potentially improving black-grass control, this is likely to have had a negative effect on the national yield. During the 2000s deep tine systems (including 'subcasting') have become more common. It is uncertain whether or not the deeper loosening of the soil achieved with these approaches has reduced or removed the yield penalty from not ploughing. Therefore, while this cannot be quantified with certainty, assuming an average of 2% of the crop area per year changing from ploughing to reduced tillage (as seen for wheat) and taking the 7% average yield penalty with

non-inversion seen in the STAR project, the reduction in yield improvement due to establishment method is estimated at 0.006 t/ha per year for the period from 1994 to 2011.

Chamen (2011) observed that a lower degree of soil compactness may be required for oilseed rape compared to cereal crops, and noted that where soil compaction is reduced through the absence of trafficking yield responses of 33% (Hamilton *et al.*, 2003) to 90% (Chan *et al.*, 2006) have been reported in oilseed rape in Australia. The sensitivity of oilseed rape to compacted soil was also observed in pot experiments where spring rape was grown at a range of soil bulk densities (Hess, 2012). However, a greater sensitivity of spring rape over spring wheat was only observed as soil strength increased with soil drying. This study also found evidence that oilseed rape may be able to exploit pores through hard layers more effectively than wheat.

3.5.9. Rotations

The CropMonitor survey highlights a sharp decline in the proportion of oilseed rape crops sown following a break from oilseed rape of 4 or more years, between the late 1980s (when few crops were sown with less than a 4 year break) and the late 1990s (Figure 112). The main increase was in oilseed rape crops sown following a break of 2 or 3 years. This change partly coincided with the rapid decrease in national oilseed rape yield, and may have been an influencing factor. Between the late 1990s and late 2000s there was also an erratic but slight further decrease in the proportion of oilseed rape crops sown following a break of 4 or more years, with a corresponding increase in crops sown following a break of only 1 or 2 years. However between 2008 and 2010, during which time the national oilseed rape yield trend has shown a strong increase, there is just a hint that the trend towards increased oilseed rape cropping frequency may have been slowing.

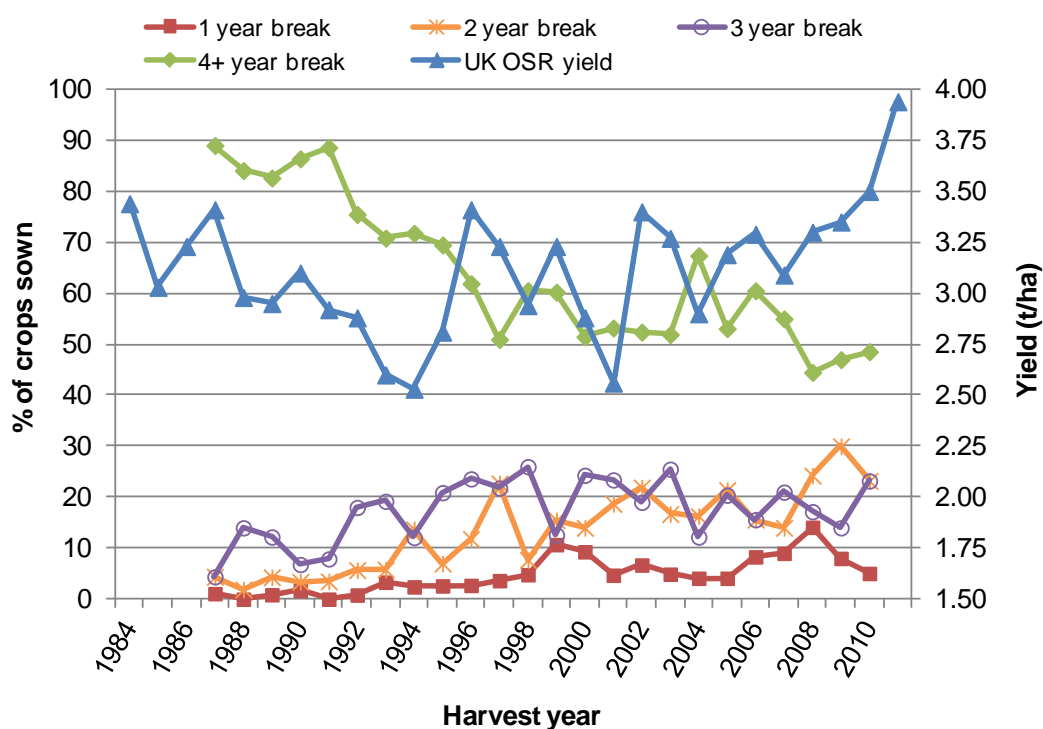


Figure 112. Proportion of oilseed rape crops in England sown following a break from oilseed rape of 1, 2, 3 or 4+ years.

A survey of farm crops by NIAB TAG in 2010 suggested that rotations with a three year break from oilseed rape are common amongst arable farmers, although rotations that are tighter than this, including alternating wheat and oilseed rape crops, are not uncommon on combinable crop farms.

A review of the impact of growing crops in short rotation or monoculture undertaken by Bennett *et al.* (2012) demonstrated that a wide range of crops grown in these ways (including oilseed rape) often suffer from yield decline compared to those grown in longer rotations. The review also noted that the practice of growing crops in short rotation or in monoculture is becoming increasingly prevalent in conventional agriculture due to a range of factors including economic market trends, technological advances, government incentives and retailer and consumer demands.

Research into the impact of rotational intensity on the performance of oilseed rape in the UK is limited; however recent data from Stobart (2011) would support the assertion that tight oilseed rape rotations are constraining yield. Data collected within HGCA project RD-2003-2922 'Impact of Previous Cropping on Winter Oilseed Rape', in which a range of crop sequences involving oilseed rape and wheat only were evaluated in an 8-year field experiment, suggest a reduction in yield of about 12% (0.46 t/ha) for a high intensity oilseed rape rotation (wheat alternating with oilseed rape giving 50% inclusion in the rotation) compared to first ever oilseed rape crops (Table 26a). There is evidence that the size of the yield penalty varies in relation to rotational intensity; with a yield penalty of 6% (0.20 t/ha) for oilseed rape grown with a 1 year gap, and an 18% (0.61) t/ha penalty for continuous oilseed rape, compared to oilseed rape grown with a 2 year gap (Table 26b).

Table 26a. Reduction in seed yield with short oilseed rape rotations compared to first ever oilseed rape crops (mean of 2006 and 2007 seasons). Source: HGCA project 2922

Cropping frequency	Yield (t/ha)	Yield (%)
First ever OSR	3.90	100
OSR 1 year in 2	3.44	88
Continuous OSR	3.22	82

Table 26b. Effect of cropping frequency on oilseed rape seed yield (mean of 2007, 2008 & 2010 seasons). Source: HGCA project 2922

Cropping frequency	Yield (t/ha)	Yield (%)
OSR 1 year in 3	3.36	100
OSR 1 year in 2	3.16	94
Continuous OSR	2.75	82

These findings are similar to those presented in Orlovius (2003), based on research by Sieling *et al.* (1997), which suggests a yield loss of approximately 0.5 t/ha comparing data from a 50% inclusion of oilseed rape in the rotation with that inferred for a first ever oilseed rape crop. Further findings published by Christen & Sieling (1999) from Germany and Cathcart *et al.* (2006) from Canada also support the assertion that yields of oilseed rape increase in line with the length of rotational break. The findings of both Stobart (2011) and Christen & Sieling (1999) suggest that very long (at least a 4 year break from oilseed rape) and very short (or monoculture) rotations are likely to have the greatest impacts on oilseed rape yield potential.

The causes of yield decline under different rotations remain unclear; however, the following factors have been implicated:

- Previous crop: Christen and Sieling (1999) indicated that the influence of the directly preceding crop may modify the effect of cropping frequency on oilseed rape performance within the rotation. Highest oilseed rape yields tended to occur following peas as a preceding crop (followed by barley and wheat as preceding crops).
- Agronomy: Stobart (2009) highlights the contribution of volunteer plants to yield reductions, as older varieties that grow as volunteers may be lower yielding than current varieties, as well as harbouring pathogens and pests, or competing directly with the sown crop.
- Diseases: a range of pathogens including club root (*Plasmodiophora brassicae*), stem canker (*Leptosphaeria maculans*), Verticillium wilt (*Verticillium longisporum*) and black leg (*Rhizoctonia solani*) have been associated with short rotations in oilseed rape (Christen & Sieling, 1999).

Recent research by Mills *et al.* (2009) has also associated increased levels of the root pathogens *Olipidium brassicae* and *Pyrenochaeta spp.* with short rotation UK oilseed rape crops. The broad scale impact of these specific pathogens in relation to rotational intensity still requires further study.

Based on data from HGCA project 2922, yield losses are estimated at 3%, 6%, 12% and 18% for oilseed rape crops with a break of 3 years, 2 years, 1 year and no break (continuous) respectively, compared to crops with a break of 4 or more years. These could, however, underestimate the yield loss for short rotations maintained over a longer period. Using the proportions of the national crop sown following a break of 3 years, 2 years and 1 year according to CropMonitor, the reduction in national average yield potential (compared to 100% of the oilseed rape crop following a break of 4 or more years) has been estimated (Figure 113). The loss in potential yield has increased from about 0.01 t/ha in 1987 to more than 0.12 t/ha in 2010, equivalent to about 0.004 t/ha per year.

Case study evidence

It is clear from the case study farm data that there is no single agronomic factor that can be linked to the improving oilseed rape yield trends observed since the mid-2000s. However, two farms in Aberdeenshire provide an interesting contrast. Both farms are on medium soils, plough routinely and cropping includes wheat, barley and oilseed rape. On the first farm (Aberdeenshire 1), average yields have increased sharply since 2005 (Figure 114). This coincided with a lengthening of the rotation to enable the break between oilseed rape crops to be extended from 1-2 years to more than 4 years. Although not present in all fields on the farm, this change was partly in response to concerns over clubroot. Varieties with resistance to the disease have also been grown on part of the crop area. On the second farm (Aberdeenshire 2), yields appear to have been plateauing since about the mid-2000s. Here clubroot is widespread, and only varieties with resistance to the disease are grown, but the rotation has shortened since 2005 with a gap of only 2 years between oilseed rape crops compared to a gap of 4 or more years up until 2004.

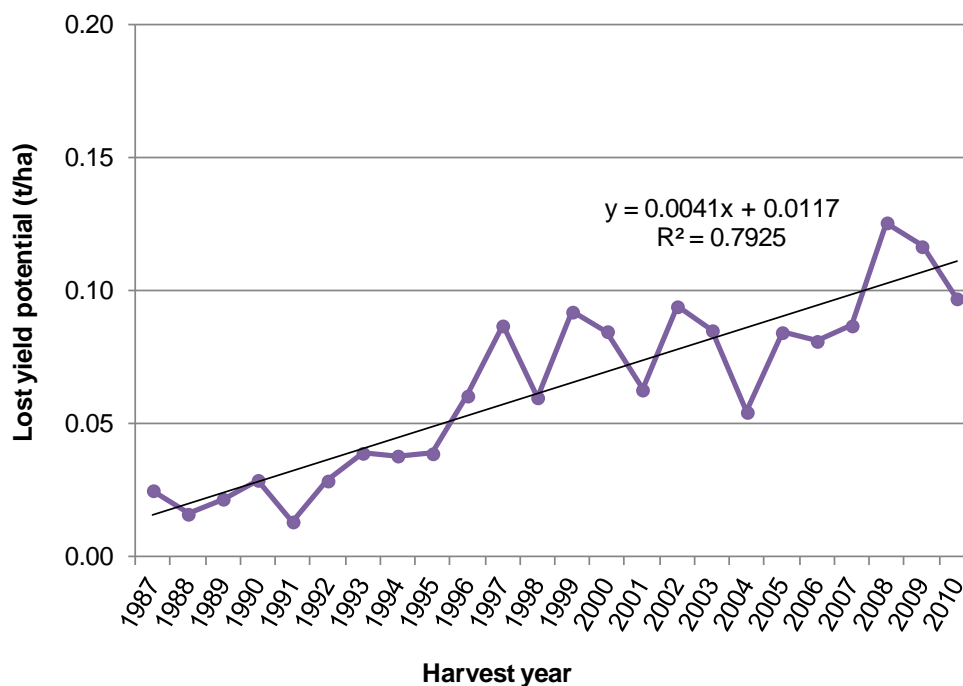


Figure 113. Calculated loss of national yield potential due to shortening oilseed rape rotations between 1987 and 2010 ($x = 1$ for 1987; $P < 0.001$; SE slope 0.0004, intercept 0.0064).

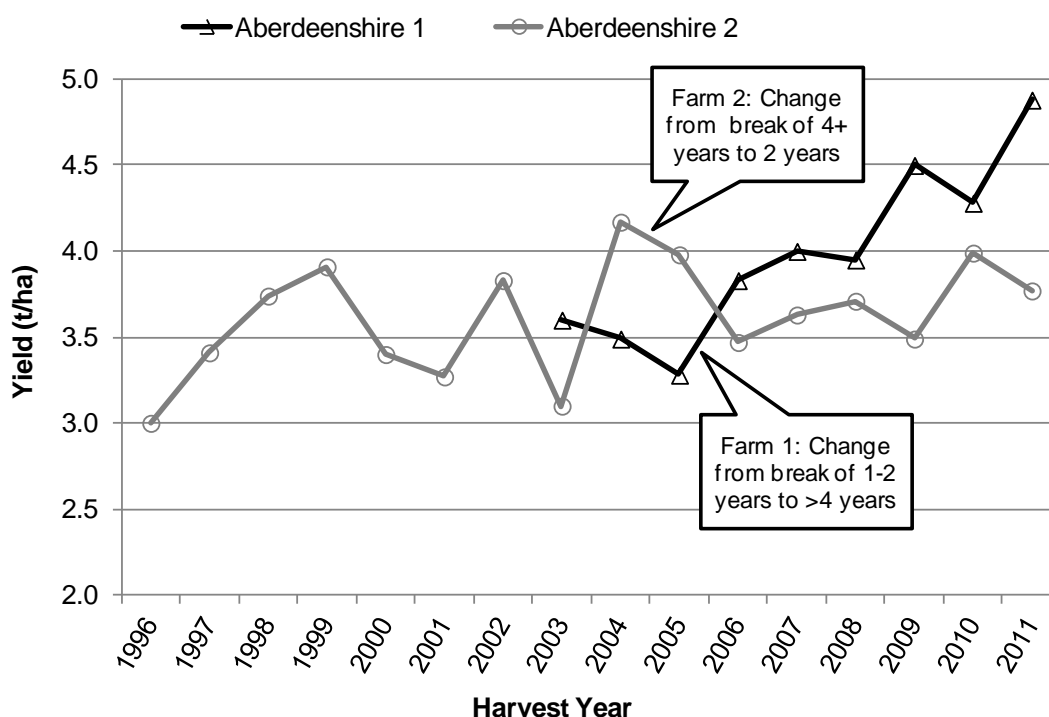


Figure 114. Comparison of oilseed rape yield trends for two Aberdeenshire case study farms that made opposing changes to oilseed rape cropping frequency during the mid-2000s.

3.5.10. Sowing dates and seed rates

It is evident that there has been a trend on farm towards earlier planting for most autumn-sown combinable crops. Although no national survey data is available, this is thought generally to be the case for oilseed rape also. However, the gradual decrease in the winter barley area since the

1990s and consequential slight increase in the area of oilseed rape following wheat has meant that this can vary from year to year depending on the earliness of the wheat harvest. In experiments conducted prior to the introduction of double-low varieties, Bowerman & Rogers-Lewis (1980) observed that optimum winter oilseed rape yields were obtained by sowing in the first 3 weeks of September, with yields depressed by sowing in August or in late September onwards. Leach *et al.* (1994) reporting experiments conducted on single- and double-low varieties in the 1980s also reported no overall yield advantage to August compared to September sowing.

Winter oilseed rape yields were compared for three sowing dates (late August, early September and mid-September) in the 1998/99 season, using three varieties (one open-pollinated, one variety association and one restored hybrid) and two seed rates (80 and 120 seeds/m²) at five sites across England and Scotland (Carver *et al.*, 1999). At individual sites the highest yielding sowing date varied from the earliest to the latest. Overall, the middle sowing date gave the highest yields and the latest sowing date the lowest, with the mean difference between them about 0.3 t/ha (8%). It appears that similar yields can be achieved within a range of sowing dates between mid-August and mid-September, and therefore any change in sowing dates that has occurred over the period from 1984 to 2011 is unlikely to have had much overall impact on the national yield trend.

Establishment of oilseed rape has always been problematic, with the small-seeded crop highly sensitive to seedbed texture, soil moisture and early predation by pigeons and slugs. Seed rates and target plant populations have changed considerably over time. Early recommendations (MAAF, 1984) were for seed rates in the order of 7.0 kg/ha, equivalent to 140 seeds/m², targeting 80 plants/m² in the spring but anticipating high field losses. Field experiments at the time indicated a sharp yield decrease below this and either a decline or a plateau in yield with higher populations. Such seed rates would now be regarded as excessive, carrying a high risk of lodging if conditions for establishment were favourable and the majority of the sown seeds emerged and survived the winter. By the 1990s the generally quoted seed rate had reduced to 120 seeds/m² and growers capable of achieving fine seedbeds were progressively reducing rates. Elsewhere in Europe seed rates were generally lower, typically 3.5 kg/ha in France and as low as 2.0 kg/ha in Germany.

The introduction of hybrids in the mid-1990s was accompanied by advice to sow at 60-70 seeds/m² (3.0-3.5 kg/ha), to address the greater plant height and biomass of the early hybrids and to account for the higher cost of hybrid seed. This gave many growers the confidence to try lower seed rates for conventional varieties, especially those with weaker ratings for standing ability, and a number of breeders started to recommend rates of 5 kg/ha, or 90-100 seeds/m², for individual varieties at risk from lodging. For RL trials, 120 seeds/m² was specified until the mid-late 1990s, when the seed rate for conventional varieties was reduced to 100 seeds/m² and 70 seeds/m² was confirmed for

hybrids. For 2011 sowing a recommendation of 40 plants/m² in spring was introduced, with maximum seed rates of 70 seeds/m² for hybrids and 80 seeds/m² for conventional varieties.

Few studies of population effects on yield have been reported on modern varieties but the HGCA Oilseed Rape Guide (2012) now recommends target populations of 25-35 plants/m². Recent studies at NIAB TAG National Agronomy Centres in Norfolk and Hampshire have demonstrated the ability of oilseed rape to produce compensatory growth, (Stobart, personal communication) for the popular variety Castille, using a range of seed rates from 50 to 400 seeds/m² and row widths from 12.5 to 50cm. Very little evidence of interaction with yield was observed, with the exception of the lowest seed rate and widest row widths, where low spring populations (<30 plants/m²) resulted in yield depression.

In summary, the modern history of oilseed rape has been characterised by a progressive reduction in sowing rates, driven by the need to reduce the risk of lodging and a desire to save seed cost. While the more recent studies suggest that this has been achieved without a yield penalty, except in cases of very poor establishment, this conflicts with the early studies that identified a rather well defined optimum of about 80 plants/m² in spring. Growers will of course continue to use their own judgement on seed rates, depending on soil type and seedbed conditions.

3.6. Discussion

3.6.1. Key factors influencing wheat yield trend

Between 1980 and 2011 the trend in UK average farm wheat yields shows two distinct phases: a steady improvement from 1980 to 1996 and since then a period of stagnation. The evidence reviewed indicates that the observed trends are not attributable to just one or two factors. Instead, a number of variables have had an impact, and the yield trends are the net result of their combined effects. Key factors that have contributed to the trend in each of the two phases are summarised in Table 27. Some of these are considered to have changed after about 2002, so the 1996 to 2011 period has been subdivided. Factors for which it has been possible to estimate their effects do not account for all of the yield trend in either phase, but a number of other variables are highlighted as potentially important and justify investigation in more depth than was possible in this initial study.

From 1980 to 1996 the average annual increase in UK farm yields was equivalent to 0.105 t/ha. The evidence indicates that there was effective uptake of new wheat varieties on farm, delivering an increase in yield potential of about 0.05 t/ha per year through genetic improvement. Therefore shifts in weather patterns and/or agronomy also contributed about 0.05 t/ha per year to the yield increase. Changes to agronomy that are likely to have impacted on yields include:

- A reduction in second or subsequent wheats, and increase in peas/beans and oilseed rape as break crops, resulting in a decline in take-all levels. On average this accounts for 0.015 t/ha per year (30%) of the remaining 0.05 t/ha per year yield improvement;
- A gradual move towards earlier drilling of winter wheat, accounting for 0.003 t/ha per year (6%) of the yield improvement;
- An increase in ploughing at the expense of minimal tillage, accounting for 0.001-0.002 t/ha per year (2-4%) of the yield improvement;
- A slight increase in the optimum N fertiliser dose for new, higher-yielding varieties. This could account for a 0.006 t/ha per year reduction in yield improvement.

Survey data that began in 1990 show an increase (up to 1996) in the proportion of crops receiving fungicide treatment at 'T2'. This period was also notable for the introduction of new, more effective fungicides. Available disease and yield response data do not indicate a quantifiable impact on the yield trend, but a positive contribution is likely. The extent of S deficiency before 1990 is uncertain, but it is thought likely to have had a negative impact on improvement in national yield at this time.

Increasing CO₂ levels are estimated to have contributed to yield improvement by about 0.013 t/ha per year. Although the effects on the yield trend of changing weather pattern have not been quantified, a positive impact is indicated, notably as a result of increased sunshine hours in June. The average increase in national farm yields from 1996 to 2011 was only 0.016 t/ha per year. This is despite a potential increase of 0.05 t/ha per year being maintained through genetic improvement. In general, new higher-yielding varieties were being taken up, but there is evidence of a partial switch from feed (Group 4) varieties to those with potential to attract a premium (Groups 1-3) on farm from 1996 to 2002, which it is estimated led to a 0.01 t/ha per year reduction in yield gain. With an estimated contribution of 0.013 t/ha per year from rising CO₂ levels, the implication is that changing weather patterns and/or agronomic practices were negating much of these gains.

A number of changes to agronomy are likely to have had an impact on the yield trend, some of which were positive and some negative. The most important of these are as follows:

- A steady switch from ploughing to non-inversion tillage, accounting for a 0.004-0.007 t/ha per year reduction in yield improvement, partly offset by a continuing shift towards earlier drilling, accounting for a 0.003 t/ha per year improvement in yield;
- A continuing slight increase in the optimum N fertiliser dose for yield for new varieties, but with no increase in the average amount of N fertiliser applied due a rising break-even fertiliser to grain price ratio, accounting for up to a 0.006 t/ha per year reduction in yield improvement;

- A rising proportion of the wheat area being treated with S fertiliser, outpacing the increase in the area at risk from S deficiency, with a positive contribution to yield improvement of up to 0.025 t/ha per year, assuming that fields being treated were those at high risk;
- An increase in the severity of septoria leaf spot between 1996 and 2002, coinciding with the pathogen developing resistance to strobilurin fungicides and a reduction in fungicide doses applied. On average this accounts for a 0.01 t/ha per year reduction in yield improvement.

The main drivers for the changes to agronomy are likely to have been the fall in crop prices in the 1990s, the effects of EU policies and their implications for farm priorities, acting as a disincentive to invest in production and leading to a reduction in management intensity. There is though evidence that not all farms responded in this way. Farm Business Survey data show that from 1996 to 2006 the yield gap increased between farms in the top and bottom quartiles.

More recently improving crop prices and changes to EU policies have begun to refocus attention on production. Expenditure on pesticides, fertiliser, labour and machinery has risen sharply since 2004, partly due to increasing input costs. As a result of increased fungicide use (number of spray rounds and total doses applied) and drier springs, from 2002 up to 2011 the severity of septoria in crops decreased, with an estimated 0.01 t/ha per year contribution to yield improvement. There was also an increase in herbicide use, but in response to rising problems with resistant black-grass rather than improving economic prospects. Investment in labour and machinery by farms in the top yield quartile has grown more rapidly than for farms in the bottom quartile but even for this group average yields have recently shown signs of plateauing. Despite a return to more intensive crop management, the national yield trend has yet to improve. It is evident that trends in routine crop inputs and operations are largely not to blame for the failure of farm yields to respond.

A number of potentially significant changes in weather patterns are evident from the late 1990s to 2011. For April there has been a trend towards decreasing rainfall and increasing SMD. It is evident that, since 2002, trends in winter wheat RL trial yields have varied between soil types, regions and sowing dates in a way that is most easily explained by differences in the risk of soil moisture limiting yield. Although the rising trend in June (and July) sunshine hours continued through to 2011, the estimated duration of grain fill has fallen by about 3 days since 1980, with the total number of sunshine hours during grain fill appearing to have plateaued since the mid-1990s. As observed in France by Brisson *et al.* (2010), it seems likely that changing weather patterns have had a significant negative impact on the national wheat yield trend over the last two decades.

In addition to weather patterns, there are factors for which it has not been possible to estimate their impact due to lack of data but that may have had a negative effect. Most notable of these is soil compaction, but also of potential relevance are UV-B levels, soil pH, under-drainage, seed rates

and timeliness and targeting of inputs and operations. Petersen *et al.* (2010) identified a few agronomic factors in Denmark that have not been significant in the UK, but again highlighted management intensity as a possible factor in proportion of the yield gap that was unexplained.

Table 27. Factors contributing to the national wheat yield trend from 1980 to 2011.

Period	1980-1996	1996-2002	2002-2011
	Yield gain + or loss - with estimate of t/ha per year. 0 neutral, () uncertain		
Farm Yield	+0.105	+0.016	
Genetic potential	+0.05	+0.05	
Variety choice	0	-0.01	0
Agronomic effects			
Nutrition N	-0.006	-0.006	-0.006
Nutrition S	(-)	+0.025	0
Disease control	(+)	-0.01	+0.01
Rotation	+0.015	0	
Cultivation	+0.001 to +0.002	-0.004 to -0.007	
Sowing date	+0.003	+0.003	
Rising CO₂ levels	+0.011	+0.011	
Weather and/or other factors	+0.030 to +0.031	-0.040 to -0.043	-0.045 to -0.048

3.6.2. Key factors influencing oilseed rape yield trend

The UK average farm yield trend for oilseed rape shows three phases over the last 28 years: a period of decline from 1984 to 1994 following the introduction of double-low varieties, very erratic yields from 1994 to 2004 and a period of improving yields since 2004. The evidence indicates that the yield trends observed reflect the combined effects of a number of variables that have impacted on the oilseed rape crop. The main factors that have contributed to the trend in each of the three phases are summarised in Table 28. These account for most but not all of the trends in yield, and other variables are highlighted as potentially important and worthy of further investigation.

From 1984 to 1994 the average rate of decrease in national oilseed rape yields was equivalent to 0.040 t/ha per year. During this time, yield potential was increasing by about 0.048 t/ha per year as a result of genetic improvement. Although it only accounts for a proportion of the area sown, with the rest made up of farm-saved or imported seed, certified seed data indicate that the uptake of the highest-yielding new varieties was poor prior to 2004, for understandable reasons. It is estimated that from 1984 to 1994 over half (up to 0.031 t/ha per year) of the annual improvement in genetic yield potential was not being deployed on farm. Although the actual split of the national cropped area between winter and spring oilseed rape is not available for this period, an estimate based on

the certified seed area occupied by spring varieties indicates a variable increase in the spring rape area, which would equate to an average reduction in yield improvement of 0.009 t/ha per year.

Changing weather patterns and/or agronomy account for a yield decline of about 0.05 t/ha per year from 1984 to 1994. Several shortfalls in agronomy are evident from 1984 to 1994, which would be expected to have limited yields. These include:

- A steep decline in the amount of N fertiliser applied, nearly 30% for spring applications over the 10 years. This accounts for a reduction in yield improvement of around 0.02 t/ha per year;
- The extent of S deficiency in the 1980s is uncertain, but responses were seen in some crops by the early 1990s. It is likely therefore to have led to an increasing yield loss prior to 1994;
- An increase in oilseed rape cropping frequency within rotations, accounting for 0.004 t/ha per year reduction in yield improvement;
- Relatively low fungicide use, especially in autumn, reflected in high levels of light leaf spot and pod diseases in farm crops in some years. This is likely to have had a negative impact on yields in some years, but with limited data it is not possible to quantify any trend with certainty.

Analysis of weather data revealed correlations between oilseed rape yield and rainfall, sunshine hours and maximum temperatures in April. The period from 1984 to 1994 saw increasing rainfall and decreasing sunshine during April. Two possible explanations for a negative yield impact have been suggested, but the most likely reason is poor seed set through reduced cross-pollination or as a result of decreased photosynthesis. This, plus other factors for which it has not been possible to quantify their impact such as increased varietal susceptibility to lodging, rising numbers of wood pigeons and relatively high levels of TuYV are likely to account for the remaining yield decline of 0.027 t/ha per year.

From 1994 to 2004 the average increase in national farm yield was only 0.022 t/ha per year. Poor uptake of higher-yielding new varieties continued, with an average of about 0.038 t/ha per year of the 0.048 t/ha per year genetic yield gain not being realised. Between 1994 and 2004 there was considerable year to year variation in the actual or estimated area of spring oilseed rape, which it is estimated may have resulted in a reduction in yield improvement of about 0.003 t/ha per year. The combined effects of weather and agronomy therefore account for a positive contribution to the yield trend of about 0.015 t/ha per year.

The period after 1994 saw a continuing increase in oilseed rape cropping frequency in rotations, accounting for a 0.004 t/ha per year reduction in yield improvement. However, EU policies and

falling crop prices were a disincentive to intensive oilseed rape production. The consequences of this included a switch to lower-cost establishment methods, notably autocasting and shallow non-inversion. Although it is not possible to quantify the impact of this change reliably due to a lack of data, it can be estimated to account for a 0.006 t/ha per year reduction in yield improvement. As a further economy, there was also an increase in the use of farm-saved seed.

Despite lower crops prices, from 1994 to 2004 there was an increase in fungicide and insecticide use in the autumn, but a reduction in the proportion of crops treated at the flowering timing. There is little evidence of overall increasing levels of stem or pod diseases during this period, and the incidence of light leaf spot decreased, but levels of phoma leaf spot and stem canker were high in some years. The net effect of these changes on the yield trend is estimated to have been neutral. The area of crop at risk of S deficiency was increasing, but the area treated with S fertiliser was also rising, with a fall in the national yield loss and a likely positive contribution to the yield trend, assuming that the fields receiving S were those at highest risk of deficiency.

Since 2004 farm yields have risen by an average of 0.075 t/ha per year. Seed certification data indicate better uptake on farm of new higher-yielding varieties, with variety choice now contributing positively to yield improvement. The reduction in the spring oilseed rape area has also made a positive contribution to yield of about 0.008 t/ha per year. Improving crop prices have led to reinvestment in production, including inputs, labour and machinery. Farm Business Survey data show that farms in the top yield quartile have been spending progressively more on pesticides than those in the bottom quartile. Consequences of the renewed production focus have included:

- An increase in the number of fungicides applied, notably the proportion of crops treated at the flowering timing in summer;
- A decrease in the incidence of phoma leaf spot and severity of pod diseases in summer, although this may be as much to do with changing weather as fungicide use;
- An increase in herbicide use, but this may partly be a response to increasing problems with resistant black-grass.

The increase in oilseed rape cropping frequency and shift from ploughing to non-inversion have continued, together accounting for a potential 0.01 t/ha per year loss of yield improvement, although this may be an over-estimate as the yield effects of deeper non-inversion methods such as subcasting are uncertain. The area of the crop receiving S fertiliser is now sufficient to account for that considered to be at high risk of S deficiency, and no impact on the yield trend is indicated, although this assumes that the fields that are being treated are those most at risk of deficiency.

With a clear trend towards sunnier and drier weather in April over this period (prior to the dull, wet conditions in 2012), part of the remaining yield improvement can be attributed to a favourable

weather pattern. Other agronomic factors that may have contributed positively include increased use of insecticidal seed treatments and the impact of lower seed rates and fungicides with growth regulatory activity on management of the crop canopy and lodging control. The positive impact of these factors may be larger than the 0.015 t/ha per year indicated, as at the same time, agronomic factors such as soil compaction and soil-borne diseases may have had a negative effect on yields.

Table 28. Factors contributing to the national oilseed rape yield trend from 1984 to 2011.

Period	1984-1994	1994-2004	2004-2011
	Yield gain + or loss - with estimate of t/ha per year. 0 neutral, () uncertain		
Farm Yield	-0.040	+0.022	+0.075
Genetic potential	+0.048	+0.048	+0.048
Variety choice	-0.031	-0.038	+0.014
Spring OSR area	-0.009	-0.003	+0.008
Agronomic effects			
Nutrition N	-0.02	0	0
Nutrition S	(-)	+0.027	0
Crop Protection	(-)	0	(+)
Rotation	-0.004	-0.004	
Cultivation	+0.003	-0.006	
Weather and/or other factors	-0.027	-0.002	+0.015

3.6.3. Potential to increase national average yields

Using Farm Business Survey data, it is possible to estimate the extent to which national average farm yields could be improved using existing technology. An estimate was made of the effect on the national average yield (mean for 2004-2009) of raising the average yields of the bottom, lower and upper middle yield quartiles to the level of the quartile(s) above, and raising the average yields of the top quartile by 10% for wheat and 15% for oilseed rape. The latter values were based on the average % improvement required to increase yield to the level of the quartile above. Details of the calculations can be found in Appendix Tables 5 (wheat) and Appendix Table 6 (oilseed rape).

The biggest single impact on national average wheat yield would have been achieved by raising the average yield achieved by the upper middle quartile to that achieved by the top quartile (adding about 0.37 t/ha to the national average yield). Raising the average yield of the bottom, lower and upper middle quartiles all by one quartile, and average yield of the top quartile by 10%, would have increased the 6 year mean national average wheat yield by 15% (1.1 t/ha) to around 9.0 t/ha.

The biggest single impact on national average oilseed rape yield would have been achieved by raising the average yield achieved by the bottom quartile to that achieved by the lower middle quartile, or the upper middle quartile to that achieved by the top quartile (both adding about 0.18 t/ha to the national average yield). Raising the average yield of the bottom, lower and upper middle quartiles all by one quartile, and average yield of the top quartile by 15%, would have increased the 6 year mean national average oilseed rape yield by 20% (0.64 t/ha) to around 3.8 t/ha.

In order to assess the potential to increase average wheat yields for each FBS yield quartile, it is useful to consider the influence of geographical, soil type or farm type differences. Natural England has defined a number of Joint or National Character Areas (NCAs) that have similar landscape character (<http://www.naturalengland.org.uk/publications/nca/default.aspx>). In many cases these also provide a reasonable division of geographical location (and therefore climate) and soil type, from which it is possible to make assumptions about the predominant farm types likely to be represented within each NCA. Figures 115 and 116 show the percentage of farms falling within each of the yield quartiles, for NCAs with at least 15 farms in at least one FBS yield quartile. In Figure 115, NCAs have been ranked (highest to lowest) in order of the percentage of farms falling within the top yield quartile. In Figure 116, NCAs have been ranked (highest to lowest) in order of the percentage of farms falling within the bottom yield quartile.

Not surprisingly, there are big differences between NCAs. Those with the highest percentage of farms within the top yield quartile include the fine loam, chalk and clay-with-flint soils in east Kent, the deep clayland soils in south Norfolk, Suffolk and north Essex, the Fen soils in Cambridgeshire and Lincolnshire and the heavy loam soils in north-east Northumberland (Figure 115). Farm types are mainly arable, either solely combinable or including roots, or in some cases with vegetable crops in the rotation. NCAs with the highest percentage of farms in the bottom yield quartile include parts of Devon and Cornwall, and areas within west Kent, East Sussex, Gloucestershire and Worcestershire, with soils that are typically variable in texture or depth, of low fertility or commonly prone to waterlogging or flooding (Figure 116). Many of these would be recognised as being more mixed farming areas, rather than predominately arable cropping.

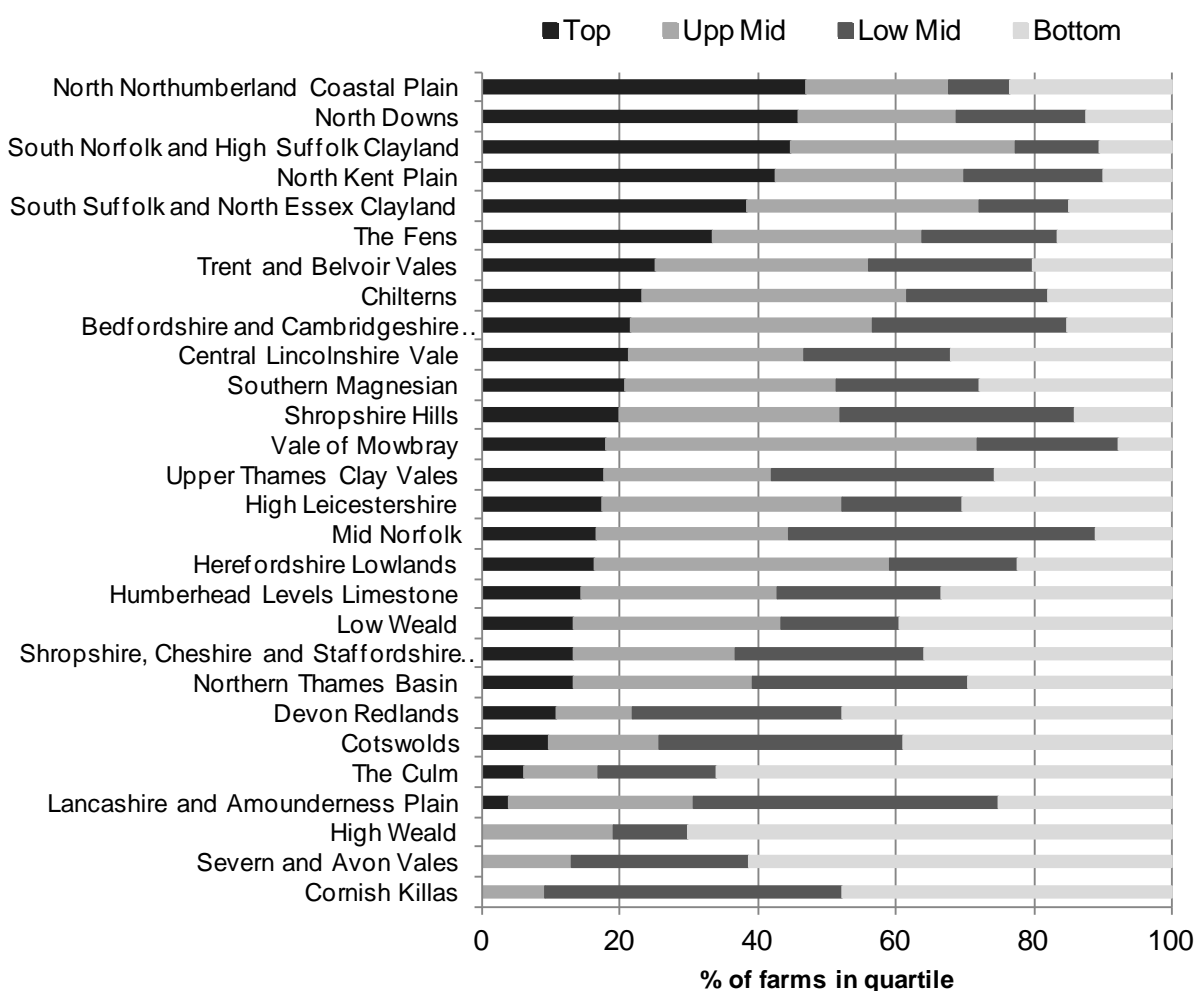


Figure 115. Percentage of farms in the top, upper middle, lower middle and bottom FBS yield quartiles for wheat for joint character areas with at least 15 farms in at least one quartile, ranked (highest to lowest) by percentage of farms in the top quartile.

This analysis goes some way to explaining the differences seen between the FBS yield quartiles, for example why the average area of wheat grown by farms in the bottom quartile is much smaller than that grown by the top quartile. It may also help to explain the observed divergence in wheat yield trends – a combination of better soils and a stronger arable emphasis providing greater potential and imperative to increase yields for the top than the bottom yielding quartile. At the same time, many of the NCAs show a fairly equal distribution of farms between the four yield quartiles, so this suggests that there is still a range of performance for farms that are ostensibly similar in their geography / climate, soil type and farm type, and therefore scope for yield improvement.

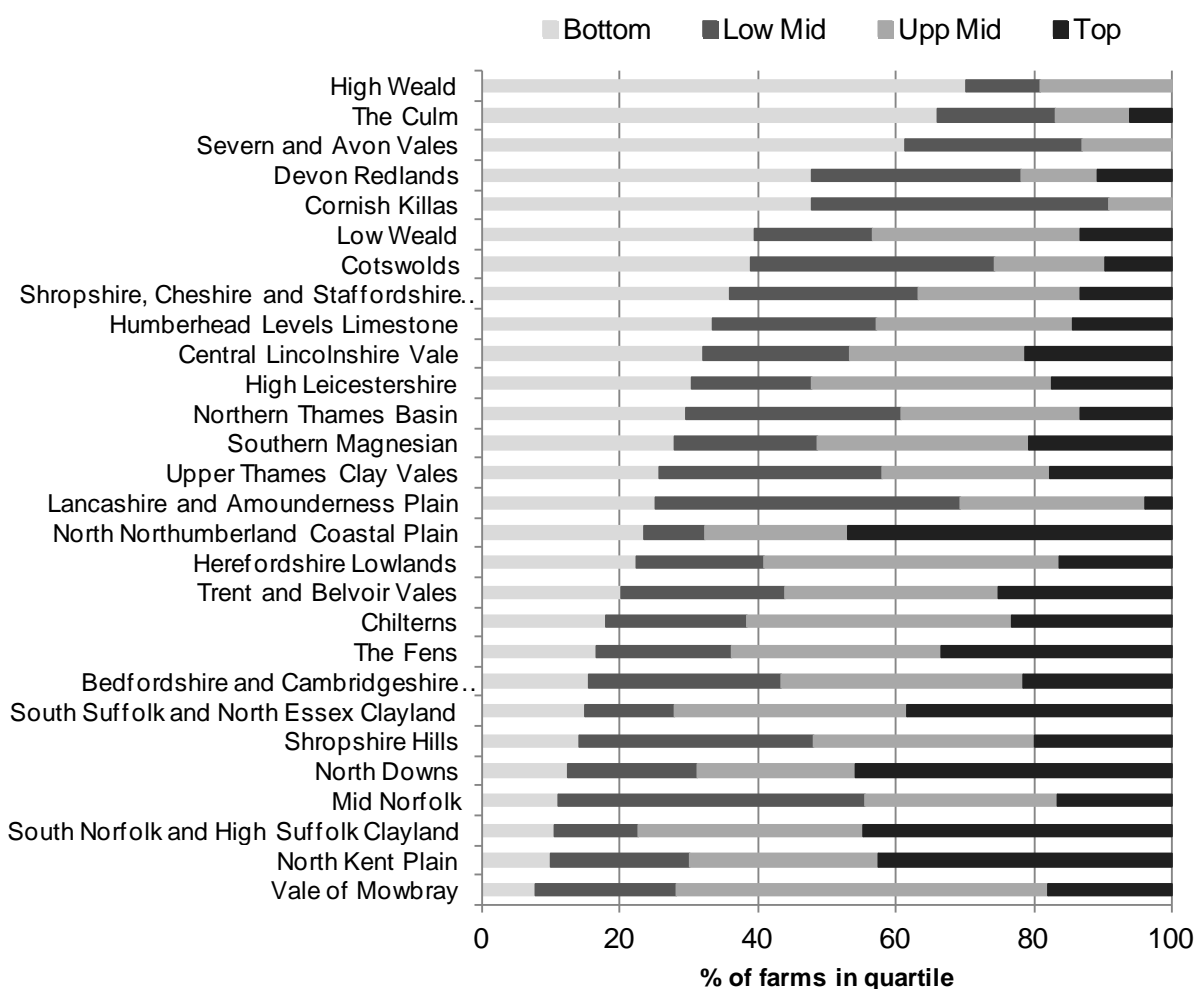


Figure 116. Percentage of farms in the bottom, lower middle, upper middle and top FBS yield quartiles for wheat for joint character areas with at least 15 farms in at least one quartile, ranked (highest to lowest) by percentage of farms in the bottom quartile.

Key agronomic opportunities for overcoming current yield limitations, and potential barriers to doing so, are outlined in the sections that follow. But how might growers achieve high yields in practice?

Benchmark yield components for an 11 t/ha crop in the UK have been proposed as 460 ears/m², 48 grains per ear and a grain weight of 50mg (HGCA, 2008). These are not unrealistic targets for most growers, and some are already achieving or exceeding this on a regular basis. Armour *et al.* (2004) examined the environmental and management circumstances that enabled a grower in New Zealand to break the 15 t/ha wheat yield barrier. The crop had an average of 490 ears/m², each with about 59 grains per ear (about 29,000 grains per m²), and an average grain weight of 53mg. The formula for a record yield was concluded to be a variety and sowing date that will lead to grain growing through the solar radiation peak, a cool but sunny summer and attention to agronomic detail so that no growth constraints apply. So, while the vagaries of the weather mean that no-one can guarantee high yields, with the right approach to its implementation, agronomy can make an important contribution.

3.6.4. Opportunities for overcoming agronomic limitations to yield

Variety selection

The Recommended Lists for winter wheat and oilseed rape provide the industry with robust, comparative information on the relative yield potential of varieties and their particular agronomic characteristics. However, the challenge facing growers is to select varieties that are appropriate for their farm, and to optimise their management. More information is needed to help match varieties to specific farm situations (site characteristics, local environment or farming system), to support uptake of those that could offer a step forward in yield (without loss of quality), and to demonstrate how, with appropriate agronomy, this could translate to a gain in profitability.

Nutrient supply

To respond to higher yield potential and support rising yield trends, the extent to which N supply limits current yields of oilseed rape and wheat must be reduced. There is likely to be a case for increasing the amounts of N fertiliser applied to at least some crops. However, with economic and environmental constraints to consider, part of the answer must be to focus on N use efficiency. Plant breeding and fertiliser technology are important, but agronomy also has a role to play, by creating conditions that will maximise N uptake by the crop. Improving the efficiency of N fertiliser use from its current average of about 60% must be a key objective. For S nutrition, more could be done to ensure that all crops that are at risk of deficiency, or are likely to give a cost-effective yield response, are identified and are receiving an application of a suitable S-containing fertiliser.

Rotations

The increase in the break crop area and decrease in second or subsequent wheats contributed significantly to wheat yield improvement prior to 1996. However, there is evidence that the rise in oilseed rape cropping frequency is limiting oilseed rape yields. A fair proportion of oilseed rape crops are currently grown with a break of four or more years. If this continues to decline, and if the incidence of soil borne threats increases, yield effects could become more significant, especially on large farms growing wheat and oilseed rape only. Efforts must continue to address these threats and wider rotations may form part of the solution. It is recognised that understandably rotations will continue to be driven by overall profitability rather than the yield potential of individual crops.

Crop protection

Crop protection metrics indicate no reduction in robustness over the last 30 years. Breeders have improved pest and disease resistance, uptake of new chemistry has been good, and numbers of active ingredients applied and application rounds have increased. Farms in the top yield quartile are spending more on pesticides (and presumably using more rather than paying more for them), but this could partly be explained by greater grass weed control costs on heavy soils. There is little evidence that a general increase in pesticide use is needed to remove yield restrictions, although

inadequate control of weeds, pests or diseases will still limit yields in challenging seasons and situations. Efforts should be focused on the threat posed by pathogen evolution, pesticide resistance and a decline in number of modes of action to our ability to sustain rising yields in future. Good agronomy relies on a combination of chemical, cultural and varietal control measures for weeds, pests or diseases. Although well publicised for weeds and diseases, this is likely to become more important for insect pests and potentially for nematodes. More should be done to evaluate and demonstrate the benefits of combining chemical and non-chemical control measures, including better linkage of research and KT that are often focused on one or the other.

Sowing date

Earlier sowing of wheat (before the end of September), and the avoidance of late sowing (after mid-October), are potentially key measures to reduce the impact of weather-related yield limitations, in particular to lessen the effects of spring or summer droughts that have occurred in several recent seasons. Drought has been a recurring feature of the UK climate, with recent drought events by no means exceptional in terms of their intensity or duration (Cole & Marsh, 2006). Extended drought periods were seen in 1990-1992 and 1995-1997. Short-term summer drought is projected to increase in most regions (except Scotland and Northern Ireland), although there is a large amount of uncertainty around this (Blenkinsop & Fowler, 2007). A recent Met Office report has concluded that the south and south-east of the UK regions are projected to experience an increase in the frequency of drought and water stress with climate change, although the rest of the UK may be relatively unaffected by changes in water availability with climate change (Met Office, 2011).

Sowing dates for wheat have been advancing over the last 3 decades, which trials indicate has contributed positively to the national yield trend. Earlier drilling is not without risks and problems, including lodging, grass weeds and elevated pest and disease threats. Some could be overcome by adjusting crop protection strategies, such as using seed treatments with activity against foliar diseases and insect pests, but even so earlier sowing will not be the right strategy for every grower to improve yield and won't be of benefit in every season. Lighter soils most at risk from drought are less affected by black-grass and are the main target for earlier sowing. Changes to rotations may be needed to avoid late sowing, following late-harvested roots with a spring crop instead of winter wheat. This particularly applies where soil conditions are poor, as it risks compounding drought risk with compaction, although spring crops themselves can of course be compromised by drought.

Soil management and cultivations

Soil management may have suffered through change being driven by what is technically possible and economically attractive rather than agronomically appropriate. New cultivation equipment and drills have saved time and fuel, and delivered effective establishment. However, the industry has

been on a learning curve with new techniques and larger machines, during which yields may have suffered in the short term. There has been too little emphasis on new soil management studies, undertaken and interpreted within the context of today's combinable crop production systems. Even though the principles may not have changed, practice certainly has. The trend towards bigger and heavier machinery is a particular concern. The full extent and impact of soil compaction at and below the depth normally disturbed by sub-soiling must be quantified, along with the state of UK soils in terms of other soil health measures such as under-drainage and organic matter content.

Management intensity

As fields and farms have increased in size, and growers have sought to simplify their management through block cropping, there is a risk that the husbandry applied to individual fields may become less well matched to their specific needs. However, Farm Business Survey data indicate that yield improvement is not necessarily compromised on farms that are growing a larger area of a crop, and that this may in part be due to greater investment in labour and machinery. 'Attention to detail', 'getting everything right' and 'continuing improvement' were articulated by practitioners as vital to achieving positive yield trends on individual farms. Approaches to this included:

- Involvement in grower groups that seek out and share knowledge;
- Engaging the whole farm team in understanding crop performance;
- Investment in training, more effective machinery or technology to capture / analyse information;
- Making more use of agronomists or specialist advisors to help improve the farming system.

A number of precision farming techniques also have the potential to help deliver better targeting of agronomy, facilitating attention to detail while improving the outputs from labour and machinery.

3.6.5. Barriers to overcoming agronomic limitations to yield

Environmental constraints and tensions

Although soil processes that influence greenhouse gas (GHG) emissions e.g. N₂O are recognised, less is known about the relative contributions of crop management factors, including N supply, and environmental drivers for these losses (e.g. Pappa *et al.*, 2011). Emissions are most likely to be reduced by a combination of two factors (1) increased crop N use efficiency and (2) the avoidance of husbandry practices associated with significant N₂O losses (e.g. Ball *et al.*, 2008). As N use efficiency can be positively correlated with yield improvement, the latter could have a positive influence by reducing N₂O intensities (emissions per tonne of grain), as well as leaching losses.

Emissions of N₂O and CO₂ from soils are highly variable. Both soil management (e.g. Ball *et al.*, 2002) and crop species (e.g. Chen *et al.*, 2002) influence N₂O emissions. The overall impact of low- or no-till on GHG emissions need to be considered in relation to soil type and structure. For

example, under no-till carbon sequestration tends not to increase to depth but it does increase near the surface (0-30 cm), improving soil structure and nutrient cycling. This benefit, however, is offset in poorly drained soils particularly by increased N₂O release, so no-till has a negative effect on GHG emissions. Under low tillage systems the emission of CO₂ from fuel usage is reduced. For example, fuel consumption under low- or no-till is invariably less than under ploughing, though the difference will depend on the soil type, the depth of cultivation and requirement for secondary cultivations. Potential fuel savings compared to average fuel consumption under a ploughing system have been estimated to range from 50-80%. This reduced consumption can substantially reduce the emission of CO₂ and other GHGs from the production and consumption of tractor fuel.

Earlier sown wheat crops should on average have a larger biomass going into the winter, and will have taken up slightly more residual N from the soil. As a consequence there may be a small reduction in leaching risk, especially on lighter soils for which earlier drilling is of greater benefit. It is likely that earlier drilling and the potential for larger crop canopies or earlier closure would reduce the growth of spring-germinating weed species, which may have a negative effect on the diversity of arable plants and associated invertebrates, and reduce feed and access for ground-foraging or ground-nesting birds. This likely tension requires further specific consideration and investigation.

Legislative constraints

For Nitrate Vulnerable Zones (NVZs), part 4 of the Nitrate Pollution Prevention Regulations 2008 (http://www.legislation.gov.uk/uksi/2008/2349/pdfs/uksi_20082349_en.pdf) establishes a limit on the amount of N (from manufactured N fertiliser and crop available N from livestock manures) that can be applied to specified crops. The current limit (Defra, 2009) for winter wheat is 220 kg N/ha, plus an extra 20 kg N/ha on certain shallow soils and 40 kg N/ha on milling varieties, and assumes a standard crop yield of 8 t/ha. The current limit is 250 kg N/ha for oilseed rape, 30 kg/ha of which may be applied in the autumn and 220 kg/ha in the spring, and assumes a standard crop yield of 3.5 t/ha. However, for both crops the limits allow for increased application rates where yields are higher. For wheat an additional 20 kg N/ha is permitted for every tonne that the expected yield exceeds the standard yield. For oilseed rape an additional 30 kg N/ha is permitted in spring for every half tonne that expected yield exceeds the standard yield. So, if it can be demonstrated that yield potential is higher, current regulations should not be a barrier to increasing N supply to support higher yields. However, any reduction in NVZ limits could constrain yields in future.

Pesticides are a key component of the efficient and cost-effective production of wheat and oilseed rape, and underpin current yield levels that are achieved. A number of important active ingredients have been lost in recent years, or are under threat, as a result of changing European legislation, particularly Regulation (EC) No 1107/2009, which followed the revision of Directive 91/414/EEC, and the implementation of the Water Framework and Drinking Water Directives. Withdrawal of

pesticides not only reduces opportunities to control pests, weeds or diseases but places extra pressure on those active ingredients that remain available. In some cases this may increase their chance or level of detection in water. In addition, there may be an increased risk of resistance development through over-dependence on the same mode of action for control. An integrated approach to regulation of chemical crop protection is essential to maintain yield improvement, including the timely approval of new active ingredients to replace the loss of existing ones.

Under the new legislation European Authorities have to define a list of Candidates for Substitution, considered to be more hazardous than alternatives, by the end of 2014, with active substances on the list then subject to a Comparative Assessment at the Member State level. It is accepted that there should not be a significant economic disadvantage to the withdrawal of product authorisation and that resistance management should be considered. It is not clear if a declining or stagnating yield trend would be considered a significant economic disadvantage, but it is essential that an adequate diversity of pesticide options remains for the management of key threats to yield. The Sustainable Use Directive, adopted by the European Parliament and EU Council in 2009, involves a series of measures aimed at establishing a framework to achieve sustainable use of pesticides. An important component of the Directive is Article 14 on Integrated Pest Management to be implemented by member states by 1st January 2014, with priority given wherever possible to non-chemical methods of crop protection. IPM invariably sounds good in principle, but in practice is far less attractive. However, an integrated approach to crop protection, including further improvement in varietal resistance, will be important for the mitigation and management of resistance risks.

Uptake of technologies

On the whole, the application of technological developments does not appear to have been much of a constraint. However, the ability to exploit genetic potential at a whole field or farm level, rather than simply at the small plot scale at which progress is currently assessed, appears to be a barrier. Increased yields that are obtained under relatively uniform conditions in trials do not appear to translate well to the wider range of local environments and management systems on farms. Another consideration is that trial yields may be achieved at a relatively high input level and cost, which if transferred to farms may incur additional or undesirable environmental or economic costs. The extent to which, in the future, new plant breeding technologies, including genetic modification, might aid the realisation of improved yield potential on farm through novel solutions to current limitations could be important.

3.6.6. Quality and end use considerations

For wheat and oilseed rape a case has been made for increasing the supply of N to crops and the area treated with S fertiliser. Increasing N dose or S application should not reduce the grain quality of wheat, and for breadmaking varieties it may improve the chance of meeting the required milling

specification. Dampney *et al.* (2006) showed that, at the higher Nopt values applicable to modern higher yielding Group 1 and 2 wheat varieties, grain protein contents were mostly between 12.5% and 13.5% (average 12.76%), close to the 13% typically required to obtain a full breadmaking premium. In these trials 38% of modern varieties would have needed more than 280 kg N/ha in order to achieve 13% protein, and 25% would have needed more than 300 kg/ha (Dampney *et al.* 2006). For crops grown for bioethanol production, for which high starch and low protein grain is preferred, avoiding overuse of N fertiliser may become vital as N production and use accounts for about 70% of the GHG emissions from growing wheat. A lower N dose may be justified if there was a premium for high starch content, but this may reduce alcohol yield (HGCA, 2010).

For oilseed rape there is well documented evidence that increasing N decreases the % oil content of the seed. Chalmers (1989), working with the early double-low variety Ariana, recorded an almost linear reduction in oil content from 48.0% down to 45.3%, over a spring N dose range from 0 up to 420 kg N/ha (Figure 117) but with comparatively little further reduction in oil content at N levels above 300 kg/ha, equivalent to the loss of 0.64% oil content per 100kg of N. Knight and Bingham (2006) also observed a reduction in oil content with increasing spring N dose and an increase in seed chlorophyll concentration. The decreased oil content was compensated for by increased overall seed and oil yield, but increased chlorophyll presence in the oil can have an adverse effect on oil quality and has been a matter for concern in some seasons. Recent unpublished work by NIAB TAG on a set of modern hybrid and conventional varieties indicated a reduction in oil content of 1.17% over a spring N dose range of 0-300 kg N/ha. The trial gave a maximum yield of 5.49 t/ha at 200 kg N/ha, with little yield increase or oil reduction above 200 kg N/ha. Gross output (yield adjusted for the value of the oil content) shows a parallel response curve to that of yield, demonstrating that loss of oil content, over this range, is matched by increasing yield (Figure 118).

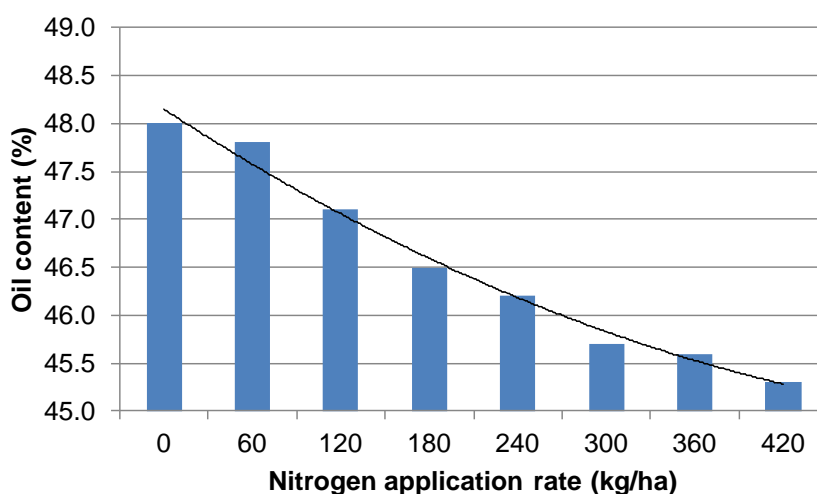


Figure 117. Effect of spring N dose on % oil content of winter oilseed rape (after Chalmers, 1989).

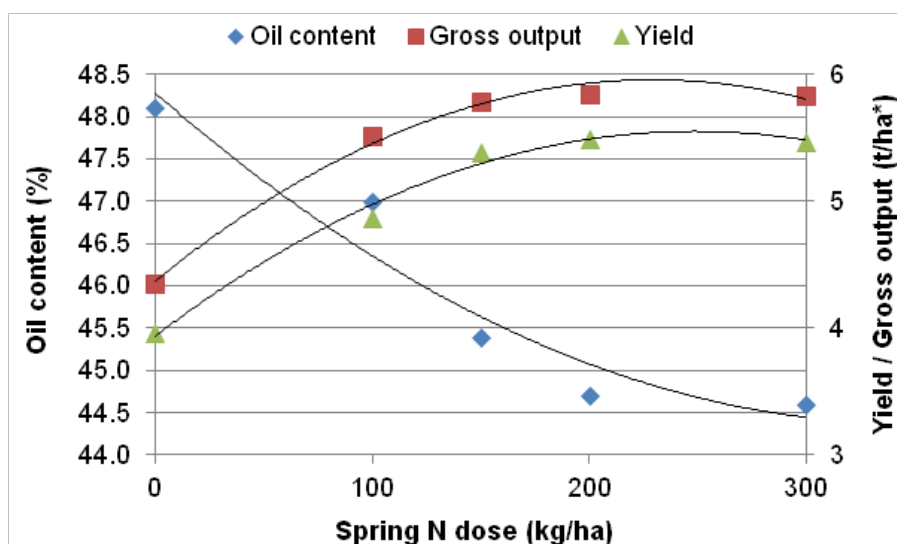


Figure 118. Oil content, yield and gross output response to increasing spring N dose (*gross output calculated as crop yield + 1.5% for every 1% oil increase over 40%). (NIAB TAG)

In contrast to the effects of N dose, Knight and Bingham (2006) found no negative impact of S fertiliser application on % oil content. Indeed applying S on a deficient site increased % oil content and there was an overall decrease in seed chlorophyll concentration with S application.

Chalmers (1989) also reported a small (2.3 μ mol) increase in glucosinolate content of the meal for a spring N dose range of 0 - 420 kg N/ha, but this is insignificant. Glucosinolates are sulphur-based molecules and their levels are elevated in response to increasing S fertiliser applications. While not associated with financial penalties there is a general drive to reduce glucosinolates to improve the suitability of oilseed rape meal for inclusion in non-ruminant livestock rations. Further extending the use of S fertiliser on deficient sites as suggested in this report is unlikely to endanger this objective.

3.7. Conclusions and recommendations

No single agronomic factor has had a clear dominant influence on trends in UK wheat or oilseed rape yields over the last 30 years. A proportion of the lost yield improvement remains unexplained, with aspects of climate change being amongst the likely causes. The data analysis indicates that plant breeding has delivered continuing genetic improvement in both crops. Relatively poor uptake of new higher-yielding oilseed rape varieties has reduced the potential for yield improvement on farm, but not necessarily profitability, as varieties that are easier to manage have enabled growers to make savings in inputs, labour or machinery. Weather patterns have had an impact, but these appear to have acted in varying and opposite directions for wheat and oilseed rape.

Apart from 1980 to 1996, when there was a positive contribution to wheat yield improvement, alterations to agronomic practices have had a number of mainly small effects. Some of these have been driven by prices or policies, with growers seeking to maximise profit rather than yield. To

restore rising yields in the face of warmer conditions, potentially more extreme weather, economic or environmental pressures and evolving weed, pest or disease threats, there is a need for some changes to farming systems, with a longer-term and more holistic approach to agronomy.

3.7.1. Specific recommendations

Short term: Getting the most from current technology

Short-term opportunities to raise farm yields involve additional knowledge transfer to address apparent shortcomings in agronomic practice. Not all growers will benefit, as many will already be employing best practice, but they may provide quick wins for others to improve crop performance.

1. Building on 'RL Plus', the outputs of the RL variety evaluation system should be supplemented by additional information, including potential interactions with soil conditions, fertility, rotation, crop environment and local climate, to guide variety selection for specific situations, recognising that limitations to performance may differ under challenging and varied farm conditions. This is both a knowledge transfer need and a gap in the current variety evaluation system.
2. Achievement of higher farm yields may require a less conservative approach to variety selection and management. Ease of harvesting and avoidance of lodging are understandable reasons why growers may reject higher-yielding varieties or hold back on seed rate and N use. Better tools and information to aid forecasting, monitoring and management of growth and lodging risk are needed, for example the use of canopy sensing technologies to target PGR treatments.
3. Various HGCA projects have studied aspects of crop husbandry that are relevant to early sown wheat crops. Key messages from these should be reviewed and brought together in a suitable format to inform best practice for the management of early sown wheat crops.
4. The proportion of wheat and oilseed rape crops currently treated with inorganic S fertilisers (40% and 60% respectively) equates to little more than that at high risk of deficiency. Although some will be receiving S in other forms e.g. organic manures, there is likely to be an area of crop, especially oilseed rape, at medium risk that isn't being treated. Updated advice on areas of the UK in which crops are at medium or high risk, and likely to respond to treatment, should be made available.
5. About 20% of soil samples tested are below the target P index for arable cropping, with 30% below the target K index. Although there is no evidence that this has contributed to yield stagnation or that the proportion of sites below target is increasing, with negative net budgets for P and K and off-take proportional to yield, there is a risk that this may change. Current soil testing technology should be checked for its effectiveness in modern arable conditions and further knowledge transfer

is needed to reaffirm the benefits of regular soil testing, to ensure effective targeting of fertilisers to fields where yield is at risk, and to avoid low P or K indices becoming a yield limitation in future.

6. This study has highlighted the consequences of responding too late to pesticide resistance. In the case of septoria in the late 1990s, fungicide doses declined on the back of low crop prices and more expensive new fungicides, with little priority given to managing risk or robustness of control. With fungicide sensitivity a continuing issue for septoria and light leaf spot, the on-going problem of resistant black-grass and emerging problems of resistant aphids and pollen beetles, it is essential to maximise awareness of risks and practical implications, especially how to manage resistance through changes to control strategy and the integration of chemical and cultural control measures.

7. While not always within a grower's control, timeliness is undoubtedly pivotal in the effectiveness of certain operations and inputs. Agronomy information tends to focus on comparison of products, doses or techniques, but the implications of mistiming for yield should be made equally accessible.

Short to medium term: Areas of uncertainty

A number of factors have been identified that may be having a negative impact on national yields, but for which information is lacking on their incidence or importance. Many are being investigated but more could be done to raise awareness or widen engagement in addressing the problem.

1. The extent to which changes in weather patterns / climate have contributed to yield trends in wheat and oilseed rape over the last 3 decades requires a dedicated investigation and analysis, including the use of suitable crop models, which was outside the scope of this study.

2. Reducing the extent to which N supply limits current yields of oilseed rape and wheat is vital to support a rising yield trend, but applying more N fertiliser is not sustainable because pollution risks and GHG emissions may increase even if efficiency of use could be maintained. Further studies are needed to show how fertiliser technology or agronomy can impact on or improve fertiliser efficiency, including interactions with soil management and rooting.

3. It is unclear whether or not plant breeding has led to increased N use efficiency in modern oilseed rape varieties, or if they require more N. The extent to which current fertiliser N doses and timing are sufficient to realise the yield potential of varieties being grown needs to be clarified

4. There is a need to raise awareness and further evaluate the contribution of pollination to yield in oilseed rape. Operation Pollinator (<http://www.operationpollinator.com/>) is addressing this, but the extent to which this is a determinant of oilseed rape yields may be underrated. There is a potential 'win-win' by addressing the challenge of simultaneously raising productivity and environmental

benefits, which could be achieved practically through greater use of pollen & nectar margins combined with crop management that takes more account of the value of insect pollination.

5. There is a critical knowledge gap with regard to the state and health of UK soils and implications for yield, including the incidence and severity of compaction at and below sub-soiling depth, the maintenance of under-drainage systems and variation or trends in soil organic matter levels.

6. Further evaluation of the incidence (location/season) of nematodes in wheat and oilseed rape is needed to understand their potential impact on crop performance, including the effects of weather, soil type, rotations and cultivations, and the implications for variety selection or plant breeding.

7. Further evaluation of short- and long-term yield implications for wheat and oilseed rape of the move from ploughing to non-inversion cultivation is needed. A recent study has indicated that penalties may be associated with the initial transition but it is unclear if this is a year affect, an unavoidable consequence or due to poor management of the transition phase. It could have particular importance for farms that use rotational ploughing as part of a cultural control strategy for grass weeds. New HGCA-funded projects on soil management may help to address this.

8. There appears to be little independent information on the extent of secondary (Mg) or trace element (Mn, B, Mo) deficiencies in oilseed rape, or on likely yield responses to their application. A full review of existing knowledge, and new data from field experiments to fill any gaps, are needed.

Medium term: Changing approach

Constraints to yield improvement have altered over time, often as a consequence of changes to cropping in response to prices or policies rather than for agronomic reasons. In some cases there may have been a price to pay in the long term for profitability in the short term. A new approach is needed to assessing and improving the longer-term performance, output and resilience of farming systems, while maintaining flexibility to respond quickly to emerging threats and new solutions.

1. Farm Business Survey data has highlighted the divergence in yield trends between farms in the top and bottom yield quartiles. Farm benchmarking is justifiably focused on financial performance, but more could be made of the data gathered in understanding differences between farms in their yield or yield trends. This could provide useful indicators of potential limiting or derestricting factors.

2. Information, tools and advice are needed to help growers 'health check' their farming system and to encourage a longer-term approach to cropping and crop management strategy. This goes beyond conventional benchmarking and includes the likely impacts of rotation, cultivation and soil

management strategy on current and future yield potential, productivity and the vulnerabilities or robustness of the farming system.

3. Precision farming techniques and technologies have the potential to improve the timeliness and targeting of inputs or operations, and to help maintain attention to detail as farms get larger. However, they also need to be more practical and accessible for small or medium-sized farms.

Long term: Preparing for the future

This study has focused primarily on looking back in order to identify some of the factors that have contributed to the failure of farm wheat and oilseed rape yields to show consistent improvement. It is vital that there is also now a focus on future yield potential, from genetic, climatic and agronomic perspectives, so that the industry is better prepared.

1. Data on farm practice, from national statistics or surveys such as CropMonitor, are invaluable as indicators of change. But there is information that is not being collected that would be useful, and other data lacks sufficient definition to fully characterise change. This would include establishment method for oilseed rape, more precise information on cultivation type and depth for wheat, seed rates, weed incidence and a more universal survey of soil and crop nutrient status. This is vital for monitoring shifts in practice, to help anticipate effects or constraints on crop performance.

2. Although this study did not examine the specific impact of changing climate, there is evidence in both wheat and oilseed rape of positive and negative impacts from higher temperatures and drier springs. These have been linked to wheat yield stagnation in Europe, and are a potential threat to our ability to raise UK yields in future. Breeding and selection of varieties suited to changing and varying environmental conditions around the UK remain an important priority.

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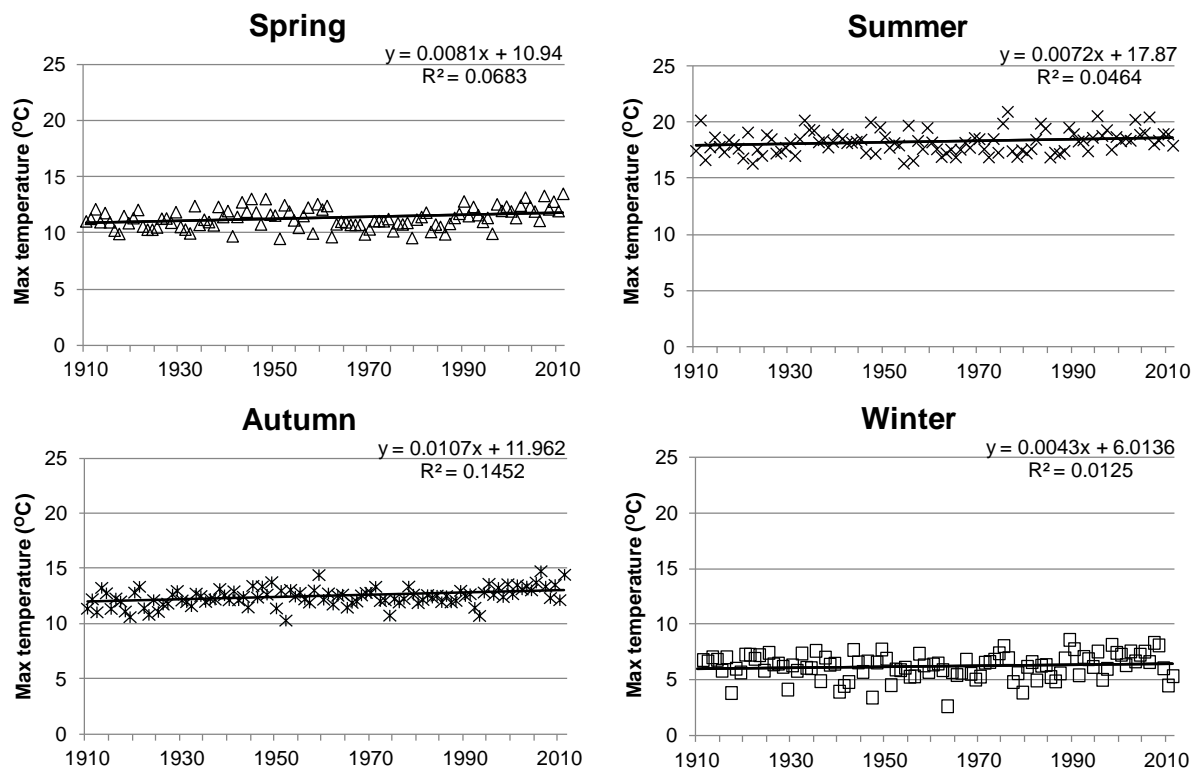
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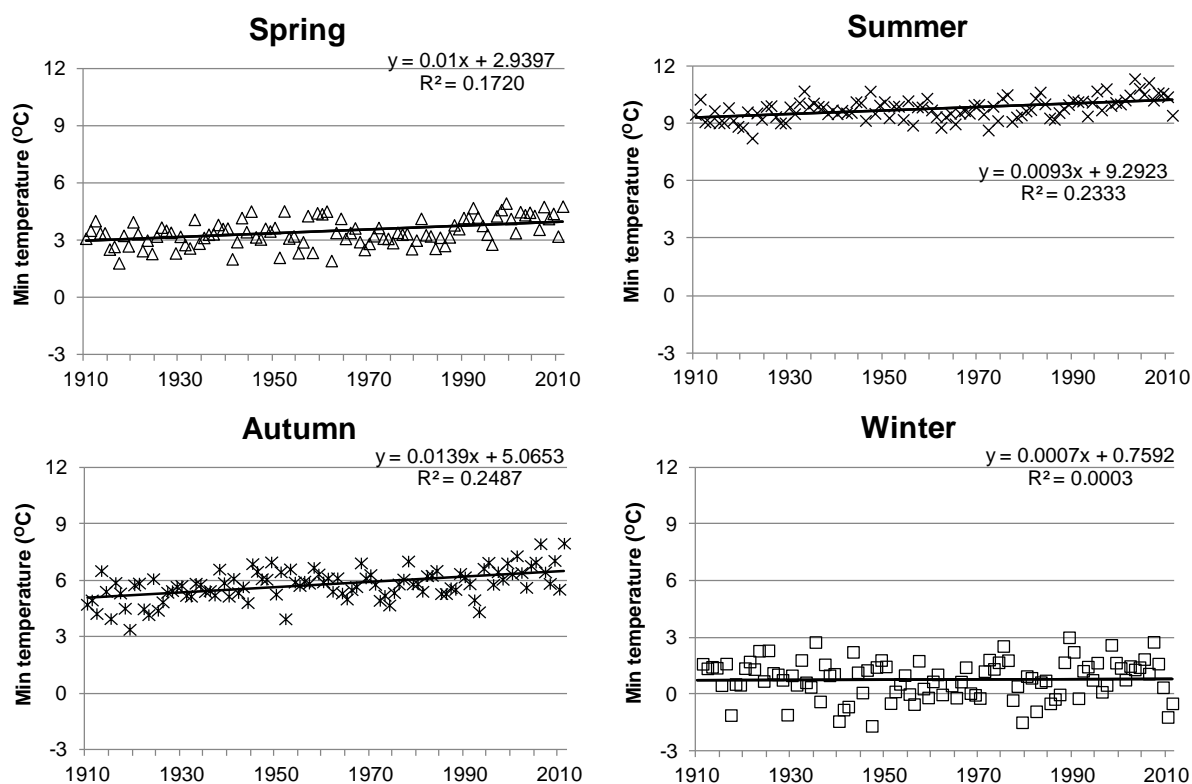
Appendix 1: Long-term weather trends and yield correlations 1910-2011

Maximum temperature



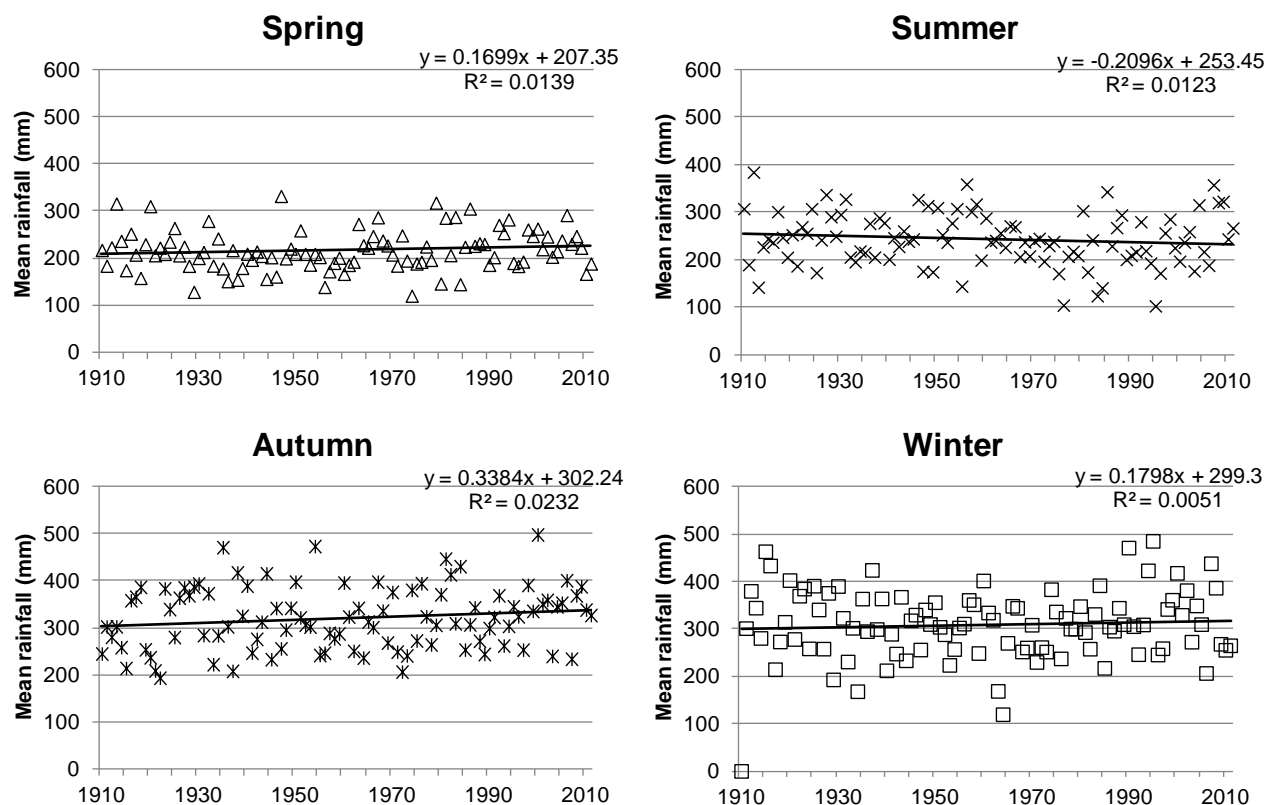
Appendix Figure 1. UK mean seasonal maximum temperatures (°C) 1910 – 2011 (x=1 for 1910).

Minimum temperature



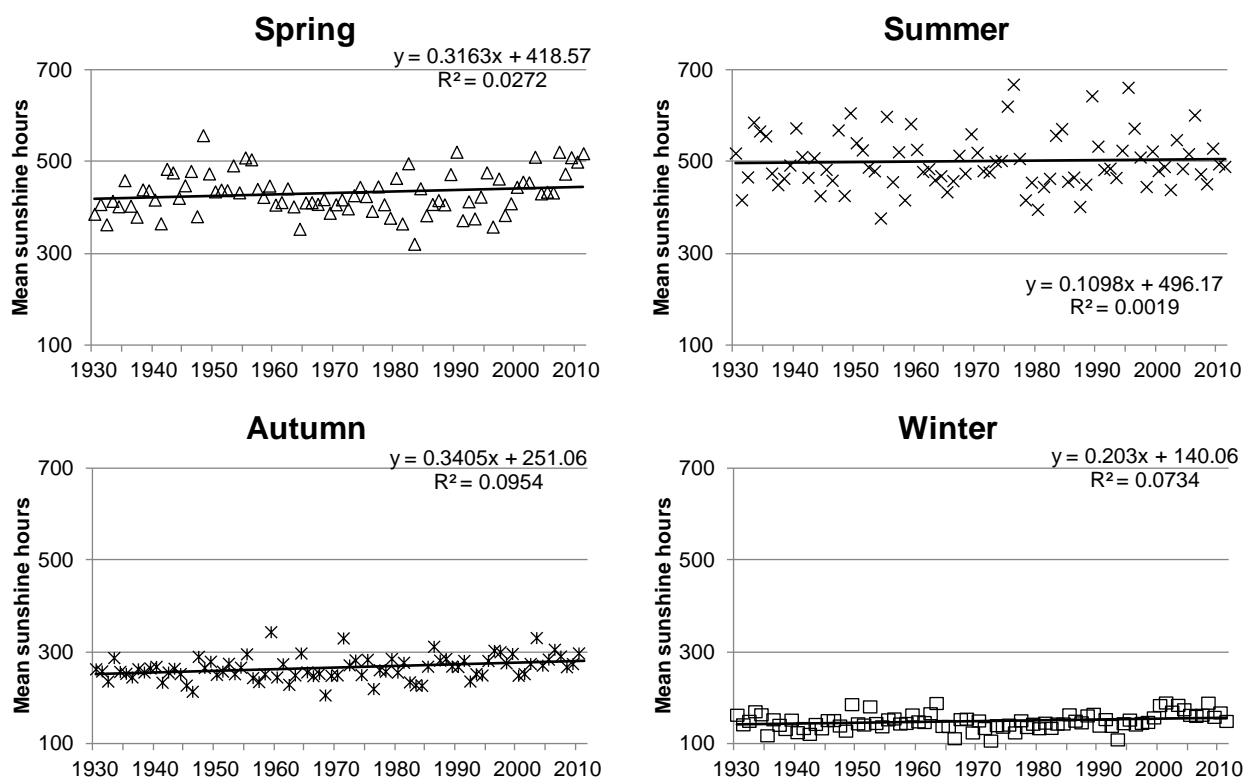
Appendix Figure 2. UK mean seasonal minimum temperatures (°C) 1910 – 2011 (x=1 for 1910).

Rainfall



Appendix Figure 3. UK mean seasonal rainfall totals (mm) 1910 – 2011 ($x=1$ for 1910).

Sunshine hours



Appendix Figure 4. UK mean seasonal sunshine hours (totals) 1910 – 2011 ($x=1$ for 1930).

Appendix Table 1 shows correlations between de-trended UK wheat yields and single monthly UK mean weather variables for the 'harvest' years from 1911 to 2011. For wheat, each harvest year ends in August and includes September to December of the previous year. Considerable caution is needed when interpreting the 1911-2011 correlations due to the large number of years covered by the analysis, during which yields would have been influenced by many other factors. However, the results are included here for completeness.

Appendix Table 1. National wheat yield correlations with UK weather, and significance levels, for 1910 to 2011.

UK	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
Rainfall	0.050	0.125	0.081	-0.046	0.080	0.067	<i>0.250</i>	-0.017	0.009	0.102	-0.169	-0.111
Sunshine	0.122	0.179	0.313	<i>0.240</i>	0.160	0.172	-0.071	0.155	0.121	-0.186	0.158	0.114
Mean Temp	0.268	0.257	0.276	-0.023	0.144	0.125	<i>0.236</i>	0.298	<i>0.201</i>	0.194	0.265	0.274
Max Temp	0.193	<i>0.217</i>	0.295	0.040	0.164	0.148	0.188	0.267	0.115	0.071	<i>0.212</i>	<i>0.221</i>
Min Temp	0.335	0.304	0.265	-0.068	0.123	0.112	0.284	0.326	<i>0.288</i>	0.366	0.347	0.346
Significance Levels	5% +ve		<i>0.196</i>				1% +ve	0.255				
	5% -ve		<i>-0.196</i>				1% -ve	-0.255				

Appendix 2: Wheat varieties representing yield improvement

Appendix Table 2. Wheat varieties representing yield improvement within nabim groups (yields shown are lifetime NL/RL trial yields).

Variety	Year first listed	Nabim group			
		Group 1	Group 2	Group 3	Group 4
Riband	1987			10.14	
Hereward	1990	9.19			
Charger	1992		9.94		
Consort	1992				
Equinox	1994				9.89
Savannah	1995				10.25
Claire	1996			10.18	
Malacca	1997	9.65			
Deben	1998			10.44	
Biscay	1998				10.52
Solstice	1999	10.17			
Xi19	1999	10.53			
Einstein	2000		10.33		
Robigus	2000			10.62	
Cordiale	2001		10.36		
Gladiator	2001				10.54
Istabraq	2001				10.69
Glasgow	2002				10.77
Battalion	2004		10.40		
Oakley	2004				11.25
Gallant	2006	10.39			
Ketchum	2006		10.68		
Warrior	2006			10.64	
KWS Sterling	2007		10.80		
Invicta	2007			10.87	
Cocoon	2008			10.90	
KWS Santiago	2008				11.30
Crusoe	2009	10.42			
Torch	2009			10.94	

Appendix Table 3. Oilseed rape varieties representing yield improvement within variety types (yields shown are lifetime NL/RL trial mean yields).

Year first Listed	Open pollinated		Composite hybrid		Restored hybrid		Semi-dwarf hybrid	
1984	Ariana	3.56						
1985								
1986	Cobra	3.77						
1987								
1988	Falcon	3.86						
1989	Envol	3.87						
1990	Bristol	4.00						
1991	Apex	4.05						
1992								
1993								
1994	Capitol	4.10	Synergy	4.43				
1995					Pronto	4.43		
1996	Madrigal	4.32						
1997	Escort	4.34	Geminii	4.53				
1998	Fortis	4.47						
1999					Royal	4.65		
2000	Winner	4.55						
2001	Expert	4.69			Exact	4.68		
2002	Castille	4.67						
	Es Astrid	4.75						
2003					Excalibur	4.83	PR45D01	4.57
2004								
2005					Flash	4.84		
2006	Vision	4.88			PR46W21	4.99	DK Secure	4.73
2007	DK Cabern	5.03					PR45D05	4.79
2008	Sesame	5.13					DK Sequoia	4.84
2009							Thorin	4.93
2010					Marathon	5.22	Troy	5.09

Appendix 3: Winter oilseed rape seed certification data

Appendix Table 4. Winter oilseed rape seed certification statistics (final seed weights as % of crop totals) and 'lifetime' yield estimates from trials

	Mean yield	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	(2011)
Falcon	3.87	33.9	25.9	16.4	5.6	8.2	1.1	4.4	2.8			1.3											
Lictor	3.65	23.3	2.7																				
Libravo	3.62	17.8	10.7	2.2	1.8																		
Capricorn	3.37	6.5	9.8	14.2	11.4	6.4	1.6	1.8	2.5	0.4	1.0	0.4	0.6										
Samourai	3.66	6.5		3.5																			
Tapidor	3.53	3.1																					
Silex	3.48	2.8	1.2																				
Cobra	3.8	2.0	1.3		1.6	0.9																	
Score	3.41	1.9																					
Link	3.62	1.0																					
Susana	3.59	0.4																					
Aztec	3.67	0.1	0.4																				
Rocket	3.7	0.1	10.1	3.8	2.5	1.1	0.8																
Envol	3.88		25.8	18.1	2.4																		
Idol	3.78		10.0	0.7		0.2																	
Eurol	3.78		1.5																				
Apache	3.72		0.3	12.9	6.4	0.8																	
Inca	3.86		0.1	1.1	2.4	3.2	1.2	2.5	0.1	0.7													
Bristol	4.02			16.8	19.3	14.9	6.4	1.8	1.1														
Prospa	3.72			2.3	2.5																		
Lineker	3.63			2.2																			
Cobol	3.76			1.2																			
Askari	3.61			1.0	1.1		1.3	1.0	1.5	1.8	2.0												
Polaris	3.7			1.0																			
Arcol	3.79			0.9																			
Apex	4.05			0.1	28.0	41.9	46.5	48.6	49.8	47.1	20.9	19.2	7.4										
Mandarin	3.79				7.9																		
Express	3.83				5.1	3.9	2.8	0.9	0.9														
Gazelle	3.94				2.3	1.8	10.2	4.2	1.0	1.8	3.9												
Liberty	3.8				0.9																		
Alaska	3.9					7.7	7.7	0.9															
Navajo	3.81					3.8	1.0																

	Mean yield	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	(2011)
Commanche	3.83					2.1	2.9	3.5	0.8	2.2	3.3												
Scorpio	3.74					0.9																	
Ark	3.88					0.5																	
Corporal	3.84						3.6																
Amber	3.99						3.0	5.5	0.7														
Rapier	3.93						2.5																
Nickel	4.06						2.4																
Lizard	4							9.8															
Arietta	4.01							3.3	1.9														
Capitol	4.1							3.0	4.8		4.7												
Corniche	3.96							2.7	1.3														
Limbo	4							1.7															
Jazz	4.07							1.6	0.7														
Lipton	4.16								5.6	7.2	3.0	0.9	1.9										
Herald	4.16								4.2	4.7	3.9	5.1											
Ish 93/2 (H)	*								4.0														
Licrown	4.19								3.2	2.5													
Meteor	4.17								2.8	0.7													
Columbus	4.13								1.7														
Lightning	3.66								1.6	0.8													
Pronto (H)	4.43								1.5	8.5	6.4	7.6	2.5	0.9									
Contact	4.14									12.1	9.8	2.2	1.2										
Madrigal	4.32									4.9	10.3	6.5	3.1										
Boston	4.14									1.7													
Alpine	4.08									1.3													
Kansas	4.09									0.8													
Escort	4.33										10.4	16.2	12.6	3.8	1.4								
Maplus **	3.82										8.2	8.8	5.4	5.5	7.5	9.7	3.2	1.9		1.3			
Gemini (H)	4.53										5.6												
Steffi	3.76										1.3												
Erox **	*										1.2												
Fortis	4.46											11.9	13.3	7.2	3.0	0.6							
Pyramid	4.09											5.6	1.1	1.0									
Triangle (H)	4.31											3.1											

	Mean yield	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	(2011)
Tenor **	*											2.7	2.7										
Turner **	*											2.2											
Martina	3.69											1.7		1.4	0.2								
Wh2-112 (H)	*											1.5											
Shannon	4.3												11.0	3.0									
Courage	4.37												9.7	6.3	5.9								
Recital	4.43												9.6	5.8	5.9	2.4	1.5						
Canberra	4.31												8.6	11.6	8.2	5.5	1.0						
Tradition **	4.35												2.3	1.2									
Disco (H)	4.47												1.7	5.9	2.3	1.8							
Winner	4.54													25.2	30.2	33.6	10.7						
Pollen **	*													5.2	8.2	6.4	3.2	2.1					
Tequila	4.32													4.6	2.2	0.6							
Ontario	4.44													2.1	0.1		1.7	0.1	0.7				
Ibex	4.14													1.3									
Georgina	4.28													1.3									
Caracas	4.52														7.6	5.5	4.4	1.2					
Zeruca **	*														3.0	1.8							
Expert	4.69														2.0	12.3	12.8	7.2	5.0	1.9			
Concept	4.44														1.8								
Hearty	3.89														1.6	3.7	7.9	3.2		3.9			
Nkbravour.	4.68															4.6		2.9		1.9			
Nkvictory.	4.71															2.9							
Aragon	4.4															1.6							
Labrador	4.6															1.6		0.7					
Sw Gospel	4.55															1.5							
Castille	4.67																20.4	27.7	44.9	38.7	19.7	8.7	1.2
Lioness	4.62																15.8	14.0	7.5	2.2	0.6		
Es Astrid	4.75																4.0	4.9	7.7	5.2	2.4	2.3	6.6
Atlantic	4.52																2.7	1.5					
Trabant **	*																1.8						
Carito	4.51																1.5						
Ladoga	4.53																1.3						
Catalina	4.66																	11.3					
Nk Grace	4.64																	8.8	3.7				

	Mean yield	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	(2011)
Kalif	4.51																	1.8	5.2				
Komando	4.52																		14.0	2.2			
Temple	4.67																		5.7	0.7	1.8	2.2	2.5
Excalibur (H)	4.83																		3.0				
Canti Cs	4.74																		2.2				
Bastion	4.71																		0.1				
Mallory (H)	4.72																		0.1				
Pandora (NE)	4.27																		0.1				
Murray	4.55																		0.0				
Catana	4.79																			12.9	6.7	6.6	8.9
Ovation **	*																			8.9	9.5	7.1	
Dk Cabernet	5.03																			5.5	23.5	23.4	9.2
Flash	4.85																			4.8			
Epure	4.77																			3.7	2.8		
Vision	4.87																			2.8	6.3	9.6	8.3
Mendel (H)	4.34																			1.3	2.0		
V141ol.	4.17																				4.8		
Krypton	4.73																				4.6		
Osprey	4.65																				3.3	3.5	3.0
Eiffel	4.75																				3.2	1.5	
Dimension	4.82																				2.7		
Es Alienor	4.68																				1.6		
Fashion	4.95																					12.1	8.8
Sesame	5.13																					11.9	17.6
Cash	4.74																					3.8	
Es Cubic	4.71																					2.4	3.0
Oracle	4.91																					1.8	
Compass (H)	4.91																					1.2	0.8
Dk Camelot	4.97																						9.1
Rivalda	5.06																						4.3
V275ol ** (H)	4.73																						3.4
Rascal	5.01																						3.0
Abaco	4.93																						2.1
Louxor **	(4.6)																						1.9

Appendix 4: Potential to increase national average yields

Wheat

Appendix Table 5. Potential increase in national average wheat yield (based on mean of 2004 - 2009 harvests) achievable by raising average yield level of bottom, lower mid & upper mid FBS quartiles to the yield levels of the quartile(s) above them, and the top quartile by 10%.

	FBS Yield Quartile				Total
	bottom	lower mid	upper mid	top	
FBS area (ha) mean	44.7	74.1	89.4	108.9	317.1
FBS % of area accounted for	14	23	28	34	100
FBS yield (t/ha) mean	5.68	7.52	8.49	9.89	
Calculated % contribution to national average yield (7.87 t/ha)	10	21	29	41	100
	Calculated potential yield improvement (%) for bottom, lower and upper quartiles by increasing their mean yield to that of quartile(s) above				
Increase bottom to	-	32	49	74	
Increase lower mid to	-	-	13	31	
Increase upper mid to	-	-	-	16	
Increase top by 10%	-	-	-	10	
	Calculated potential <u>incremental</u> gain in national average yield (t/ha) by increasing mean yields for bottom, lower and upper quartiles to that of quartile(s) above				
Increase bottom to	-	0.24	+0.13	+0.19	0.56
Increase lower mid to	-	-	0.21	+0.31	0.52
Increase upper mid to	-	-	-	0.37	0.37
Increase top by 10%	-	-	-	0.32	0.32
	Calculated potential national average yield (t/ha) for each level of improvement				
Increase bottom to	-	8.11	8.24	8.43	
Increase lower mid to	-	-	8.08	8.39	
Increase upper mid to	-	-	-	8.24	
Increase top by 10%	-	-	-	8.19	
Cumulative effect of increasing mean yield of bottom, lower and upper quartiles to that of quartile immediately above, and top quartile by 10% (t/ha)	-	8.11	8.33	8.70	9.02

Oilseed Rape

Appendix Table 6. Potential increase in national average oilseed rape yield (based on mean of 2004 - 2009 harvests) achievable by raising average yield level of bottom, lower mid & upper mid FBS quartiles to the yield levels of the quartile(s) above them, and the top quartile by 15%.

	FBS Yield Quartile				Total
	bottom	lower mid	upper mid	top	
FBS area (ha) mean	36.1	41.1	43.1	48.2	168.5
FBS % of area accounted for	21	24	26	29	100
FBS yield (t/ha) mean	2.29	3.20	3.70	4.46	
Calculated % contribution to national average yield (3.19 t/ha)	14	22	27	37	100
	Calculated potential yield improvement (%) for bottom, lower and upper quartiles by increasing their mean yield to that of quartile(s) above				
Increase bottom to	-	40	62	95	
Increase lower mid to	-	-	16	39	
Increase upper mid to	-	-	-	20	
Increase top by 15%	-	-	-	15	
	Calculated potential <u>incremental</u> gain in national average yield (t/ha) by increasing mean yields for bottom, lower and upper quartiles to that of quartile(s) above				
Increase bottom to	-	0.18	+0.10	+0.15	0.42
Increase lower mid to	-	-	0.11	+0.17	0.28
Increase upper mid to	-	-	-	0.18	0.18
Increase top by 15%	-	-	-	0.17	0.17
	Calculated potential national average yield (t/ha) for each level of improvement				
Increase bottom to	-	3.36	3.46	3.61	
Increase lower mid to	-	-	3.30	3.57	
Increase upper mid to	-	-	-	3.36	
Increase top by 15%	-	-	-	3.36	
Cumulative effect of increasing mean yield of bottom, lower and upper quartiles to that of quartile immediately above (t/ha)	-	3.36	3.47	3.65	3.83

Appendix 5: Multivariate analysis of crop yield and weather parameters

Wheat

Appendix Table 7. Results of multivariate analysis for wheat.

Parameter	estimate	s.e.	Sig
Constant	3.06	1.36	*
MARRainfall	-0.618	0.163	**
JUNSunshine	0.567	0.162	**
DECSunshine	0.400	0.176	*
JANfrost	-0.367	0.188	
AUGMin_Temp	0.291	0.168	
MAYMin_Temp	0.292	0.175	

Note: March rainfall had atypical years in the early 1980s.

Oilseed rape

Appendix Table 8. Results of multivariate analysis for oilseed rape.

Parameter	estimate	s.e.	Sig.
Constant	2.799	0.520	***
APRRainfall	-0.1667	0.0836	
DECMin_Temp	-0.2741	0.0798	**
OCTMax_temp	0.1863	0.0808	*
MARMin_Temp	-0.1502	0.0795	
SEPRainfall	-0.1951	0.0797	*

Appendix 6: Notes from project stakeholder meeting: 16 Jan 2012, NIAB

Present	Steve Baldock (Agronomist)
	Bridget Carroll (Agronomist)
	Andrew Cragg (Farmer)
	Martin Jenkins (Farmer)
	Robert Salmon (Famer)
	John Bingham (Farmer and Wheat Breeder)
	Richard Jennaway (Breeder, Saaten Union)
	Richard Summer (Breeder, RAGT)
	Peter Werner (Breeder, KWS)
	Stephen Moss (Rothamsted)
	Ron Stobart, Jim Orson (NIAB)
	Marion Rawlins, Jemilah Bailey (Defra)
	Paul Gosling (HGCA)
	Stuart Knight, Simon Kightley (NIAB)
	Ian Bingham, Steve Hoad (SAC)
	Ben Lang (FBS, University of Cambridge)
	Mark Reader (FBS, University of Cambridge)
Apologies	Mark Means (Farmer, comments sent by email)

1. Overview of Objectives

Objectives of the project were outlined, with the final report due 31 March 2012

2. Key observations to date

Review of Evidence

Reports published in other countries indicate plateauing of wheat yields in early-mid 1990s (Europe, USA) through to 2000s (India, Argentina).

Q. Have wheat yields plateaued in Denmark or are they still increasing (as one recent presentation had suggested)?

(By email). If this really is a worldwide issue in various crops, doesn't that indicate global issues? Climate change maybe. Or have we simply reached the maximum potential yields achievable in real fields as compared with trials?

Causes identified by other authors have included input cost / grain price squeeze, agricultural policy, shift in emphasis / incentive from production to environment.

In France improvements in genetic potential offset by falling nitrogen use, changing rotations (peas decreasing, OSR increasing) and climate change impacts (summer temperatures, spring drought).

Analyses suggest that UK wheat variety yield potential increasing by c. 0.5% p.a., OSR by 2% p.a.

Yield not the only measure of variety improvement, especially for wheat (and only one of several selection criteria by farmers).

(By email). Is standing power of new wheat varieties sufficient to allow their full yield potential to be exploited?

(By email). Some farmers are getting their best yields from what are considered 'old' varieties. Is there any mileage in reviewing what it is that allows farmers to get much better than average yields from old varieties?

Limited contribution from non-variety effects to yield improvement in UK NL/RL trials since 1982 for wheat and OSR, in contrast to pre 1982 or for example forage maize and sugar beet post 1982.

Some debate over widening of gap between wheat yields in variety trials compared to on farm. Some evidence of a divergence since 1996, attributed to management and soils although some differences in agronomy noted.

Q. What assumptions were made in estimating commercial yields from trials in Ian Mackay's chart?

Q. Was use of farm saved seed accounted for in Ian Mackay's chart?

Q. Can Ian Mackay's chart be redrawn presenting just the yield difference?

Q. How does N usage compare in RL/NL trials vs commercial crops?

Q. Is the increasing yield difference partly due to tightening criteria for trials to be accepted in the RL/NL matrix i.e. are more lower yielding trials being rejected in recent years?

Q. Does the chart highlight the impact of selecting good sites for trials compared to typical range within farm fields? Or are soil management, agronomy and equipment part of the story?

(By email). If trials protocol inputs were applied to nearby fields to same standards what would yields be on those fields?

(By email). Is the potential of new varieties only realised in favourable conditions? Should there be more trials on average / poor soils?

Climate change has potential to impact through spring drought and high summer temperatures, through heat stress (e.g. wheat in India) or increased respiration losses at night (e.g. rice in Asia).

(By email). Do we know enough about temperature tolerance in grain fill and water use efficiency?

(By email). Would preventing ethylene production help yields or not?

Economics implicated through rapid decline in gross margins during mid 1990s caused by falling grain prices, leading to labour / machinery savings and reduced management in intensity.

Soil management implicated through shift in primary cultivation from ploughing to one-pass non inversion systems and increasing weight of machinery compromising soil structure. Uncertainty as to contribution (if any) to yield plateauing of changes in soil organic matter.

Q. How do changes in SOM interact with N requirement?

Q. How important is biomass compared to SOM?

(By email). Are yields plateauing in situations where there is no suggestion of soils being degraded, such as mixed farms applying FYM and using grass leys where OM is perhaps increasing?

Little evidence to suggest that declining fungicide use or increasing disease levels are a cause.

Analyses of National Datasets

Cereal production survey data for wheat and barley support plateauing of yields since 1996.

OSR yields show large seasonal variation but hard to describe as a plateau. Instead, decreasing yield trend 1984-1994, highly variable yields 1994-2004 then increasing yield trend since 2004.

Q. Is raising wheat yields the main focus of agronomists or is it other concerns e.g. maintaining control of black-grass and other grass weeds in order to be able to continue growing the crop?

Q. Is oilseed rape husbandry geared to high yields or to maximising its contribution to grass weed control in the rotation?

Q. Was the move to autocasting / minimal tillage, as a response to economics and grass weed problems (consolidated soil), a cause of yield decline / variability in 1990s?

Q. Has the introduction of 'subcasting' since mid 2000s overcome this problem by allowing above to be achieved while creating better conditions for root growth, removing the yield constraint?

Q. Could increases in Verticillium and Turnip Yellow Virus incidence cause further reductions to OSR yields?

Q. Comparing Germany to UK, in 1980-89 80% of OSR crop yields higher in UK than in Germany. In 2000-09 only 20% of yields were higher in UK than in Germany.

Is this because OSR crop is given higher priority in Germany?

Is the rotation wider?

How has the uptake of hybrid varieties differed?

Has this been influenced by unification, with yields being increased in the East?

Therefore the study needs to examine the two crops separately.

Regional wheat and OSR yield trends for England match overall UK, but indications that northerly regions bearing the brunt of the plateau / decline in the last 5 years.

Q. What is the impact of changing advice on seed rates / crop densities for wheat and OSR?

Q. What are the wheat and OSR yield trends on the Morley farm, and what has influenced them?

Yield distribution for 2011 national survey shows long tail of low yielding crops.

Q. Should agronomists tailor their advice to clients to tackle the factors that would give quickest and easiest improvements to yield? (But yields can be compromised by getting just one component wrong).

Wheat yield increases have tracked the rise in area grown since the 1880s. Area that was spring rather than winter sown is not known, but only a small % in recent decades.

In contrast, split of winter and spring oilseed rape is known since mid 1990s with indications of lower yields in years with higher proportion of spring (some of which linked to winter crop failures).

UK met data shows c. 1°C rise in average summer temperature over last 100 years, with rate of increase accelerating over time. Regional data shows 1°C rise in average June temperature between mid 1990s and 2007.

Significant positive and negative weather interactions noted for wheat and OSR yields. March rainfall, autumn/winter sunshine and mean temperatures are all positive for wheat. April rainfall is negative and April sunshine is positive for OSR. Autumn temperature is positive for OSR.

Q. Pollination is the most likely explanation for the April weather effects on OSR yield.

Q. Temperature-adjusted solar radiation would be more useful than sunshine hours.

(By email). Grain fill is around 660 to 700 day degrees from flowering. It would be good to get the radiation received per day degree during this period for a run of years.

Feed wheat price trends show start of wheat yield plateau coinciding with steeply declining and then low wheat prices from mid 1990s to mid 2000s. Prices volatile but have recovered since, too soon to determine if any impact on yield.

(By email). Are economics still a constraint to targeting yield, even with higher wheat prices?

(By email). Input costs have risen massively since 2006. Little change between 2000 and 2006.

120% rise in fertiliser costs, 60% fuel, but smaller rise in agrochemical costs.

N fertiliser use on wheat has been static since 1983 having increased in the period up to that. Yields increased up to mid 1990s, so N not limiting (and/or improving N efficiency), but this can't be ruled out more recently.

(By email). Are farmers are using sufficient N? HGCA funded research by ADAS suggested that modern wheat varieties needed more N.

Decline in OSR yield from 1998 to 1994 associated with decline in N use (significant). N use has been static or marginally increasing after that. Yield increase in recent years could be indicative of improved N management (timing).

P & K use on wheat and OSR declining since early-mid 1990s (due to application holidays) but not necessarily contributory to yield plateau as other information shows indices generally above target. (By email). How important is nutrient balance? Are phosphites and humic acids important, and can they be replaced with something cheaper?

Pulse crop shows seasonal variation since 1980s but decline in pea area largely matched by increased in beans.

Proportion of wheat sown after wheat shows steep decline between 1980 and mid 1990s, and is largely unchanged since. Wheat sown after oilseed rape has continued to increase since 1980s. (By email). Was the rise in commercial wheat yields between the mid 1970s and mid 1980s exaggerated by the decline of second wheats, because of the adoption of oilseed rape?

Substantial switch away from ploughing since mid 1990s (c. 90% falling to 60% in 2010), with reduced (non inversion) cultivation increasing from 10% to 40%, as primary cultivation for wheat. Q. What impact is vehicle / machinery weight having, on soil strength below the normal zone of measurement?

Q. Is surface soil compaction important as well as deeper consolidation?

Q. Comparable information for OSR would be useful, but not collected by CropMonitor. Ploughing may be more common in Scotland than in England.

Q. Are first 3 weeks in the life of a crop the most important in determining potential?

(By email). Is lack of rooting to blame for reducing yield potential? 2011 highlighted that soil fertility and early root growth in autumn 2010 led to yields over 13 t/ha in some fields with very little rainfall. Last season was perfect for yields of early drilled wheat with high light intensity and cooler temperatures and on moisture retentive soils enough water to tiller and grow without disease pressure. The same cannot be said after sugar beet with some crops as low as 7 t/ha. Without good conditions for grain fill these poor fields could have yielded less than 6 t/ha.

(By email). Are cultivations that would ensure uninhibited root growth too costly?

Wheat sowing dates show increase in proportion of wheat sown by end of Sept from 10% in early 1980s to 40-50% in late 2000s, with reduction in area sown after 21 Oct. Step change occurred in mid 1990s.

Total fungicide doses applied to wheat fell sharply during 1990 and 2002. Partly attributable to economics, but also the introduction of new chemistry. Resistance issues with septoria have seen steep rise in fungicide doses since 2002.

Despite fall in fungicide doses, % of wheat crops treated at key spray timings have increased since 1990, notably at T0.

Little evidence of increased severity or incidence of major foliar diseases between 1980 and 2010 in treated commercial wheat crops. Incidence of rusts has tended to be low since mid 1990s. Slight rise in septoria severity in early 2000s, most likely attributable to lag between increasing resistance and changes to fungicide practice.

No evidence of increasing levels of eyespot or take-all, if anything slight decrease since late 1990s.

Proportion of OSR crop sown before 31 Aug has varied from 30-70% since mid 1980s. Slight indications of an inverse relationship between sowing date and yield.

Autumn/winter fungicide use has increased sharply since early 1990s. Summer fungicide use plateaued between mid 1990s and mid 2000s but has increased since.

Insecticide use has increased since early 1990s.

No evidence from CropMonitor of consistently increasing light leaf spot incidence in commercially treated crops in England. Sclerotinia levels seasonably variably but no relationship with yield.

Farm Business Survey

Average wheat yields attained by top yield quartile are continuing to increase, whereas yields of bottom quartile have plateaued since 1996, resulting in an increasing difference between them.

Q. Are management practice and soil quality/fertility responsible for buffering yields on best farms?

Q. Do largest farms have best yields due to attention to detail, quality of management and/or taking advice?

Q. Can yield data be collected to compare trends on farms with 'good' and 'poor' soils?

(By email). More information on what is happening on the 'best' and 'worst' farms would be useful. Are yields not plateauing on the best farms?

But for OSR average yields of top and bottom quartiles show similar trends with difference between them not increasing since the mid 1990s.

Positive relationship between average area of wheat grown and yield quartile. Average area of OSR grown by top yield quartile also higher than area grown by bottom yield quartile in most years.

Highest average gross margins for wheat and OSR achieved by top yield quartile. Lowest average gross margins achieved by lowest yield quartile.

For wheat since 2004, top yield quartile has higher expenditure on fertiliser and sprays than bottom quartile, but no difference for seed. Top quartile also has higher expenditure on labour, machinery and contract, with difference between top and bottom quartiles increasing.

Q. This may be indicative of better timeliness and field efficiency contributing to higher yields.

(By email). Are farmers who may be increasing yields those that have sufficient equipment to ensure timeliness? Timeliness may now be more important with increasingly unstable weather and also with pesticide resistance (everything has got to be right to achieve acceptable control).

For OSR since 2004, expenditure on fertiliser and sprays has increased at a faster rate for top yield quartile. Seed expenditure marginally lower. Top yield quartile again has higher expenditure on labour, machinery and contract, with difference between top and bottom quartiles increasing.

Other Datasets and Field Experiments

2010 survey of farmers by NIAB TAG (228 crops) shows majority of yields above national average, but higher than average N application rates.

Limited rotational datasets for wheat from NIAB TAG and Rothamsted show no yield penalty for wheat sown after OSR compared to wheat sown after peas (or beans).

Results from a recently completed HGCA study show lower yields resulting from increased cropping frequency (shorter breaks) for OSR, when comparing OSR grown 1 year in 3 vs alternate OSR / wheat or continuous OSR.

(By email). A main recommendation from the project could be that more resources are needed for rotational experiments, possibly combined with soil aspects, especially controlled vs heavy traffic.